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GLENN L. MARTIN INSTITUTE OF TECHNOLOGY
WIND TUNNEL OPERATIONS DEPARTMENT

College Park, Maryland

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WIND TUNNEL ENGINEERING REPORT NO. 62-1

SURVEY OF LOW-ASPECT-RATIO
CHARACTERISTICS USEFUL IN THE DESIGN OF
CONTROL SURFACES

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SUMMARY

This report presents a compilation of characteristics obtained from subsonic experimental data for many different plan forms of low-aspect-ratio surfaces. The purpose of this compilation is to provide information for the design of ship and submarine control surfaces.

The work presented in this report was sponsored by the Bureau of Ships under Contract No. NObs - 84240. The opinions and conclusions presented are those of the contractor and not necessarily those of the Department of the Navy.

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INTRODUCTION

Information presented in this report is the result of a survey of literature of wind tunnel tests pertaining to low-aspect-ratio characteristics which are of importance in the design of control surfaces for maneuvering a vessel. During the survey emphasis was placed on low-subsonic-flow experimental data of symmetrical surfaces having the following characteristics:

1. Aspect ratio of 4 or less
2. Sweepback of 30° or less
3. Maximum thickness to chord length ratio between 9 and 18 percent
4. Reynolds number greater than 2×10^6

While emphasis has been placed on the above characteristics, some data is presented which fall outside of these limitations.

Data obtained during the survey are presented as graphs for use by the design engineer. These curves show the variation of the force coefficients, chordwise center of pressure and spanwise center of pressure (where available) with angle of attack, aspect ratio, sweep angle and taper ratio.

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SOURCES OF DATA

The primary sources of information presented in this report were David Taylor Model Basin Report 933 (Reference 1) and various NACA reports. A large number of the reports dealing with experimental results listed in the bibliography of Reference 2 were investigated. Although there are numerous publications listed in Reference 2, most of them do not fall within the limitations of this data search.

Data from David Taylor Model Basin Report 933 supplemented by tests conducted under the present contract for the Bureau of Ships at this installation (Reference 3) were the most uniform, systematic, and complete available. These reports produced practically all of the data presented on the NACA 0015 airfoil section control surfaces. Numerous planforms covering various sweep angles, aspect ratios, and taper ratios were investigated in a systematic manner in these tests.

Aside from the NACA 0015 airfoil section, the only other section on which any appreciable amount of data could be found was the NACA 0012. Most of this information was obtained from various NACA reports. While there were data available on other airfoil sections, they were not sufficient to produce the crossplots desired except for a limited amount available on the NACA 64A010 airfoil section.

Considerable experimental low-aspect-ratio data were available in the NACA literature. But, large quantities of the data were for

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asymmetrical airfoil sections and thin sections which fell outside the scope of this study. Data for wing-body combinations were also excluded from this report. When the other limitations stated in the introduction were imposed, the reports available were quite limited. Among the remaining reports were some that had to be discarded because the experimental data were not complete. That is, in some cases drag data were not available or the model support corrections were not determined during the test. The fact that the drag data were not available eliminated the possibility of computing the chordwise center of pressure. Since this was of primary interest, reports not containing drag data were rejected. Reports where support corrections were not determined or accounted for were also rejected for this information could not be compared directly with fully corrected data.

A summary of the various planforms for which information was obtained and the sources of this information is presented in Table I.

PRESENTATION OF DATA

NACA 0015 AIRFOIL SECTION

The data for the NACA 0015 airfoil section planforms are presented in two sets. The first set of data presented in Figures 3 - 17 are for the planforms having square tips, whereas, the second set of data, Figures 18 - 29 are for planforms having faired tips. Figures 3 - 10 for the square tips and Figures 18 - 22 for the faired tips present curves of lift coefficient, drag coefficient, normal force coefficient, resultant force coefficient, chordwise center of pressure and spanwise center of pressure versus angle of attack for each individual planform. The remaining figures of these sets are crossplots of the forces and centers of pressure with taper ratio, aspect ratio and quarter chord sweep as variables.

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NACA 0012 AIRFOIL SECTION

Data for the NACA 0012 airfoil section planforms are presented in Figures 30 - 48. As in the case of the NACA 0015 airfoil section, these data appear in two sets. The first set presented in Figures 30 - 36 is for the planforms having square tips. The second set is for planforms with faired tips and is presented in Figures 37 - 48.

Spanwise center of pressure data are not presented for the 0012 section planforms. The data available in the reports for these planforms were insufficient for the computation of spanwise center of pressure. Lift coefficient, drag coefficient, normal force coefficient, resultant force coefficient, and chordwise center of pressure are plotted against angle of attack for the individual planforms in Figures 30 - 34 for the square tips and Figures 37 - 41 for the faired tips. This information is then crossplotted with taper ratio, aspect ratio and quarter chord sweep as variables in Figures 35 and 36 for square tips and Figures 42 - 48 for faired tips.

NACA 64A010 AIRFOIL SECTION

A limited amount of data on NACA 64A010 airfoil section planforms are presented in Figures 49 and 50. Here again, the data available was insufficient for the computation of the spanwise center of pressure.

DISCUSSION OF RESULTS

Normal force coefficients and resultant force coefficients were computed for each planform from the lift and drag characteristics

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presented in the reports. The normal force coefficients were computed by use of the following equation:

$$C_N = C_L \cos \alpha + C_D \sin \alpha$$

The following relationship was used to compute resultant force coefficients:

$$C_R = \sqrt{C_L^2 + C_D^2}$$

When attempting to crossplot the data, it was noted that in a large percent of the cases, only three points were available for fairing a curve. Since many curves may be faired through three points, a problem arose as to the best method of fairing the data. The problem was especially serious in the case of the chordwise center of pressure where a high degree of accuracy was desired. In an attempt to solve this problem it was decided to use center of pressure curves obtained from theoretical methods as a guide for fairing the experimental data. Two methods were used to compute center of pressure data. The methods used are presented in References 1 and 4. Neither of the methods used proved satisfactory in predicting results that could be used as guides for fairing the experimental data. It was therefore necessary to fair curves through the experimental points in a manner that is reasonable and consistent with the data available.

NACA 0015 AIRFOIL SECTION

All of the data on the NACA 0015 airfoil section planforms except that presented in Figures 8 - 10 were obtained from tests run specifically for control surface studies. In these tests the models were mounted in the wind tunnel on a flat surface or ground board.

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The model then becomes a half model of a symmetrical wing with the ground board or tunnel wall introduced as a reflection plane at the longitudinal plane of symmetry. The relationship between the half model and the complete model is shown in Figure 2.

Figures 8 - 10 were obtained from tests on complete wings. The information presented in these figures is not contained in any of the crossplots. When attempting to crossplot these data, it was found that only two points could be obtained on any particular crossplot. The curves of the forces and center of pressure versus angle of attack have been retained in the report in the event that data may become available in the future which will make this information of some value.

Original center of pressure data presented in Reference 1 were plotted to a scale that was difficult to read to the accuracy desired. In order to improve the accuracy of the chordwise center of pressure and spanwise center of pressure readings, copies of the original large scale plots of Figures 39 - 88 of Reference 1 were obtained from the David Taylor Model Basin. It is felt that these large scale plots greatly improved the quality of the spanwise and chordwise center of pressure data presented in this report for the NACA 0015 airfoil section planforms.

NACA 0012 AIRFOIL SECTION

Data for the NACA 0012 airfoil section planforms come from various sources. In most cases the information was obtained from wind tunnel tests of complete wings. These were not tests that were run specifically for control surface studies as was the case in most of the 0015 series tests. Therefore, the data presented are

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not as systematic and uniform as the 0015 data. Also, spanwise center of pressure data were not available in the complete wing tests.

Chordwise center of pressure data had to be computed from the lift, drag and pitching moment characteristics presented in the reports from the following equation:

$$(CP)_{\bar{c}} = 0.25 - \frac{C_{m\bar{c}} / 4}{C_L \cos \alpha + C_D \sin \alpha}$$

Reports not containing sufficient information for this computation were rejected since chordwise center of pressure was a vital part of the survey. Several reports containing information on families of low-aspect-ratio wings were rejected because they lacked drag coefficient data or the data was not fully corrected for support strut tare and interference. These reports have been listed in the bibliography for the benefit of those who may be interested.

Generally speaking, the information presented for the NACA 0012 airfoil section planforms was obtained at lower Reynolds numbers than that presented for the 0015 planforms. In fact, most of the 0012 information is from tests conducted at Reynolds numbers lower than the limitations of the survey. Information presented in Reference 1 indicate that Reynolds number has a considerable effect on $C_{L_{max}}$ for the higher aspect-ratio control surfaces but very little effect on control surfaces where the aspect-ratio is less than 2. Chordwise center of pressure is not effected appreciably by changes in Reynolds number (See Figure 13 of Reference 1). Therefore, the data presented should be reliable up to angles of attack approaching the stall angle.

Characteristics presented in Figures 33, 34, and 41 do not

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appear in any crossplots. As was the case for some of the 0015 planforms, these curves have been retained in the report in the event that data may become available in the future which will make this information of some value.

NACA 64A010 AIRFOIL SECTION

Chordwise center of pressure values were computed for the NACA 64A010 airfoil section planforms in the same manner as they were for the NACA 0012 airfoil section planforms. Here again spanwise center of pressure could not be computed since the original tests were for complete wings.

BIBLIOGRAPHY

Reports which are felt to be very closely related to this study, but which for various reasons could not be included in this report, are listed in the Bibliography on pages 12 and 13.

CONCLUSION

This report presents the characteristics of low-aspect-ratio planforms obtained from a search of sub-sonic experimental literature. The literature search was restricted to configurations and information which could be used in the design of control surfaces for maneuvering a vessel. The information obtained from the search is presented as curves showing the variation of lift coefficient, drag coefficient, normal force coefficient, resultant force coefficient, spanwise center of pressure and chordwise center of pressure with angle of attack, aspect ratio, quarter-chord sweep angle and taper ratio.

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SYMBOLS

All data are presented in the form of nondimensional force and moment coefficients. The positive direction of the forces, moments, and angular displacements is shown in Figure 1. The coefficients and symbols are defined as follows:

A	Effective aspect ratio, b^2 / S
b	Span, measured perpendicular to plane of root section (see Figure 1)
c	Chord, measured parallel to plane of root section
\bar{c}	Mean geometric chord, $\frac{c_t + c_r}{2}$
C_D	Drag coefficient, $\frac{\text{Drag}}{q S}$
C_l	Root bending-moment coefficient, $\frac{\text{bending moment}}{q S b/2}$
C_L	Lift coefficient, $\frac{\text{Lift}}{q S}$
$C_{M_{\bar{c}/4}}$	Pitching moment coefficient about quarter-chord point of mean geometric chord, $\frac{\text{pitching moment}}{q S \bar{c}}$
C_n	Yawing moment coefficient, $\frac{\text{yawing moment}}{q S b/2}$
C_N	Normal force coefficient, $C_L \cos \alpha + C_D \sin \alpha$
C_R	Resultant force coefficient, $\sqrt{C_L^2 + C_D^2}$
$(CP)_{\bar{c}}$	Chordwise center of pressure measured from leading edge at mean geometric chord in percent of the mean geometric chord, $(CP)_c = 0.25 - \frac{C_{M_{\bar{c}/4}}}{C_L \cos \alpha + C_D \sin \alpha}$

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$(CP)_s$ Spanwise center of pressure measured from plane of root section in percent of semispan,

$$(CP)_s = \frac{C_l \cos \alpha - C_n \sin \alpha}{C_L \cos \alpha + C_D \sin \alpha}$$

q Dynamic pressure, $1/2 \rho V^2$

R Reynolds number, $\frac{\rho V \bar{c}}{\mu}$

S Planform area

Subscripts r root

t tip

V Free-stream velocity

α Angle of attack

λ Taper ratio, C_t / C_r

μ Viscosity, lb. sec/ft²

ρ Mass density, lb sec²/ft⁴ (approx. 2.0 for sea water)

Λ Angle of sweep of quarter chord line

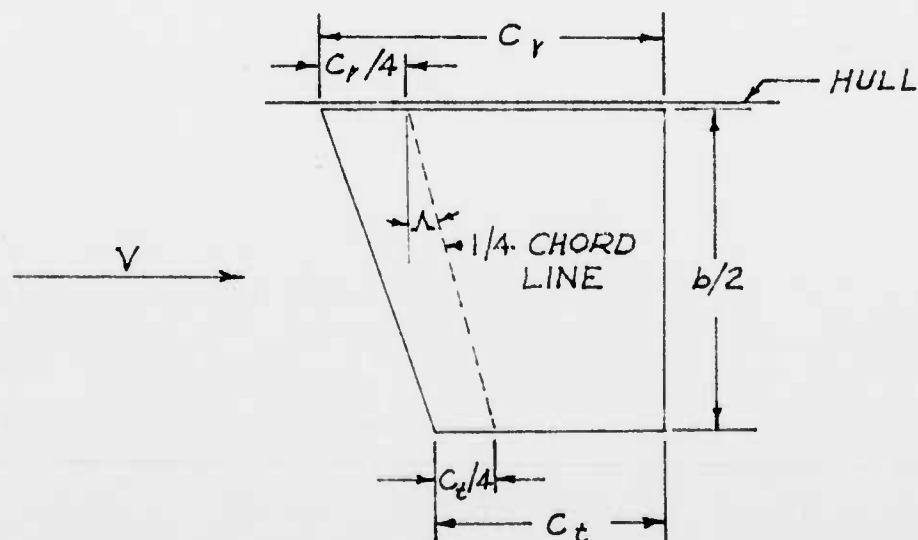


Table I
Summary of Planforms









NACA 0015 Airfoil Section Planforms						
Type Test	A	Λ Deg.	λ	R	Tip Shape	References
	1	-8	0.45	2.25×10^6	Square and Faired	1
	2	-8	0.45	2.72×10^6	Square and Faired	1
	3	-8	0.45	2.26×10^6	Square and Faired	1
	1	0	0.45	2.70×10^6	Square and Faired	1
	2	0	0.45	2.72×10^6	Square and Faired	1
	3	0	0.45	2.70×10^6	Square and Faired	1
	1	11	0.45	2.28×10^6	Square and Faired	1
	2	11	0.45	2.72×10^6	Square and Faired	1
	3	11	0.45	2.26×10^6	Square and Faired	1

Table I (cont.)











Type Test	A	Δ Deg.	λ	R	Tip Shape	References
	2	11	0.80	3.0×10^6	Square and Faired	3
	2	11	0.60	3.0×10^6	Square and Faired	3
	2	11	0.20	3.0×10^6	Square and Faired	3
	2	22.5	0.45	3.0×10^6	Square	3
	3	0	1.0	0.6×10^6	Square	5 and 6
	6	0	1.0	0.6×10^6	Square	5 and 6
	4.5	30	1.0	0.7×10^6	Square	5 and 6
	5.2	30	1.0	0.7×10^6	Square	5 and 6
	1.5	60	1.0	1.2×10^6	Square	5 and 6
	3.0	60	1.0	1.2×10^6	Square	5 and 6

Table I (cont.)











NACA 0012 Airfoil Section Planforms						
Type Test	A	 Deg.	λ	R	Tip Shape	References
	1.49	60	1.0	1.2×10^6	Square	6
	2.62	60	1.0	1.1×10^6	Square	6 and 7
	3.14	60	1.0	1.2×10^6	Square	6
	1.33	66.0	0	1.5×10^6		8
	1.33	60.2	0.125	1.5×10^6	Square	9
	1.33	53.5	0.25	1.5×10^6	Square	9
	1.33	36.9	0.50	1.5×10^6	Square	9
	1.00	71.6	0	1.5×10^6		8
	2.00	56.3	0	1.5×10^6		8

Table I (cont.)











Type Test	A	\angle Deg.	λ	R	Tip Shape	References
	3.00	0	1.0	0.6×10^6	Square	6
	6.00	0	1.0	0.6×10^6	Square	6
	3.00	6.34	0.5	0.7×10^6	Square	10
	1.34	0	1.0	1.58×10^6	Faired	7
	2.61	0	1.0	1.1×10^6	Faired	7
	4.57	0	1.0	2.0×10^6	Faired	12
	5.16	0	1.0	0.99×10^6	Faired	7 and 11
	1.34	45	1.0	1.56×10^6	Faired	7
	2.61	45	1.0	1.4×10^6	Faired	11
	2.61	45	1.0	1.1×10^6	Faired	7 and 13

Table I (cont.)







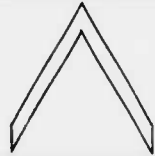





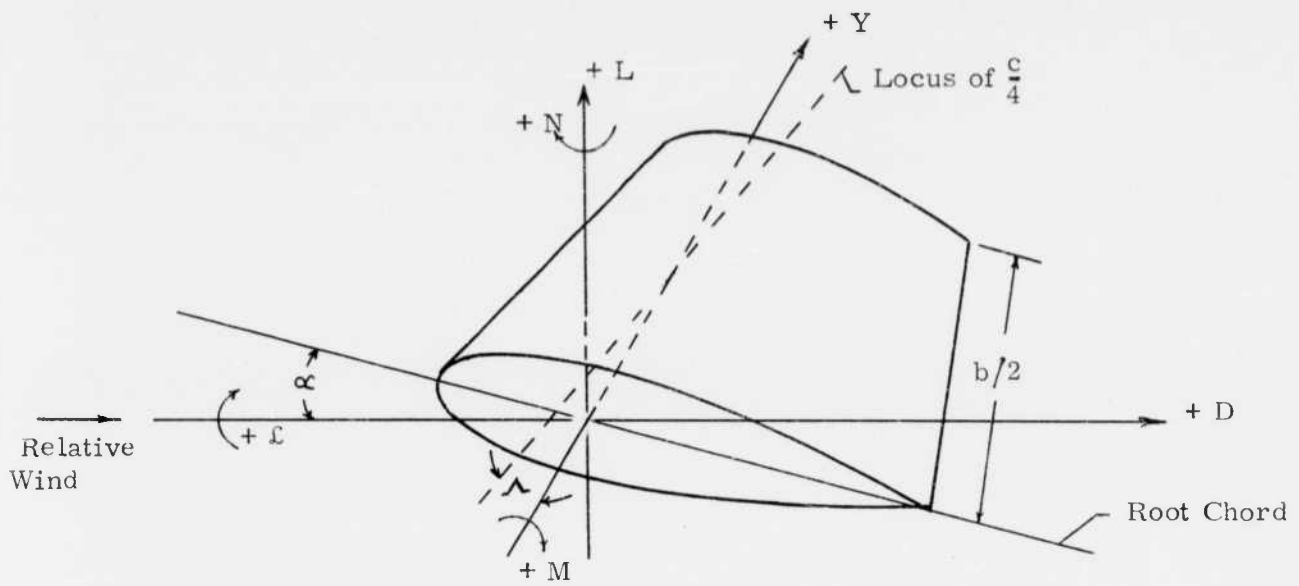
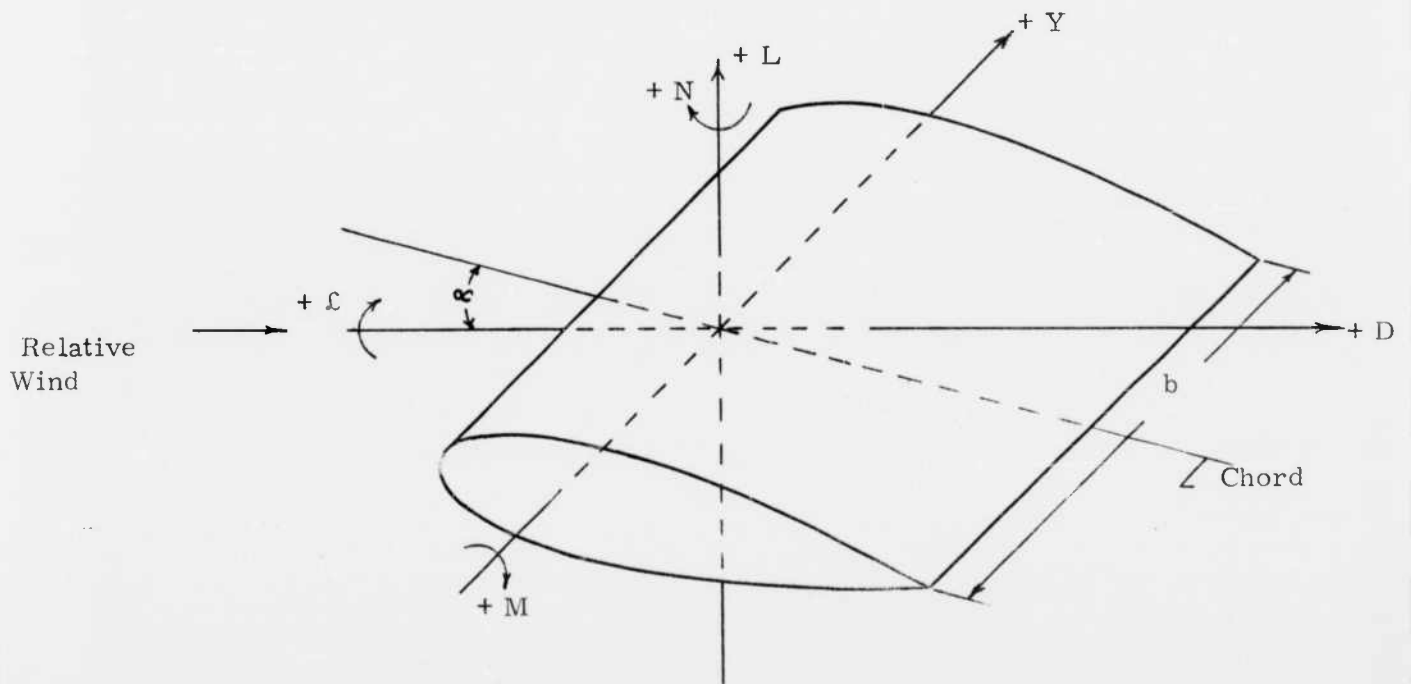
Type Test	A	\angle Deg.	λ	R	Tip Shape	References
	5.16	45	1.0	0.77×10^6	Faired	7 and 11
	2.61	45	0.5	1.2×10^6	Faired	13
	2.61	45	0.25	1.2×10^6	Faired	13
	3.00	45	0	1.5×10^6		8
	1.34	60	1.0	1.98×10^6	Faired	7 and 11
	2.61	60	1.0	1.1×10^6	Faired	6 and 7
	5.16	60	1.0	$.76 \times 10^6$	Faired	7
	5	0	0.5	1.0×10^6	Faired	14
	5	35	0.5	1.0×10^6	Faired	14

Table I (cont.)

NACA 64 A 010 Airfoil Section Planforms						
Type Test	A	\angle Deg.	λ	R	Tip Shape	References
	1.13	0	1.0	4.4×10^6	Faired	15
	2.13	0	1.0	3.1×10^6	Faired	15
	4.13	0	1.0	2.2×10^6	Faired	15

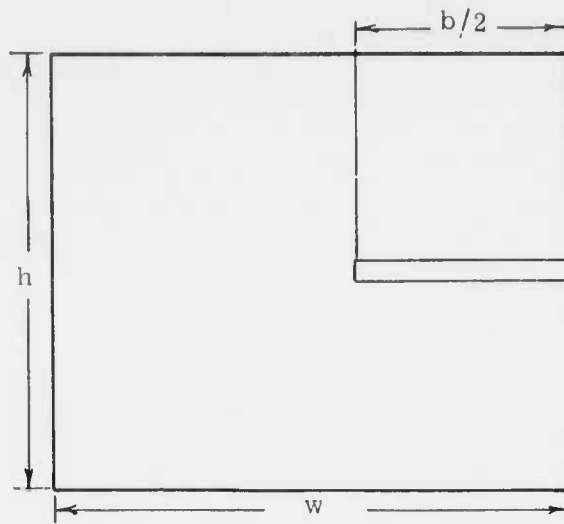


a. Control Surface or Half Model Arrangement

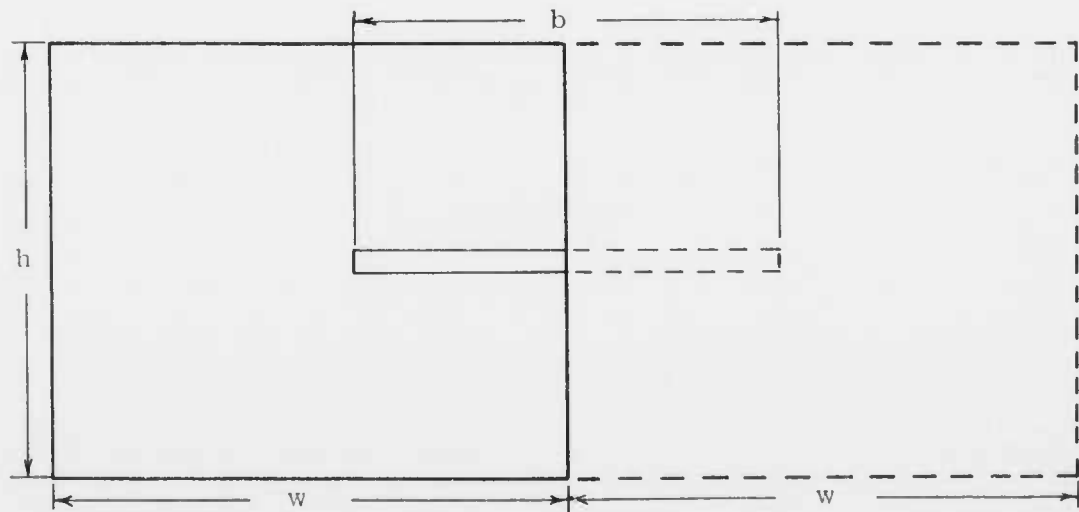


b. Complete Wing

Fig. 1. Coordinate Systems Showing Positive Direction of Forces, Moments and Angle of Attack



a. Panel or Half Model in Tunnel of Width w .



b. Complete Wing in Tunnel of Width $2w$.

Figure 2. Comparison of Half Model and Complete Model Test Arrangements.

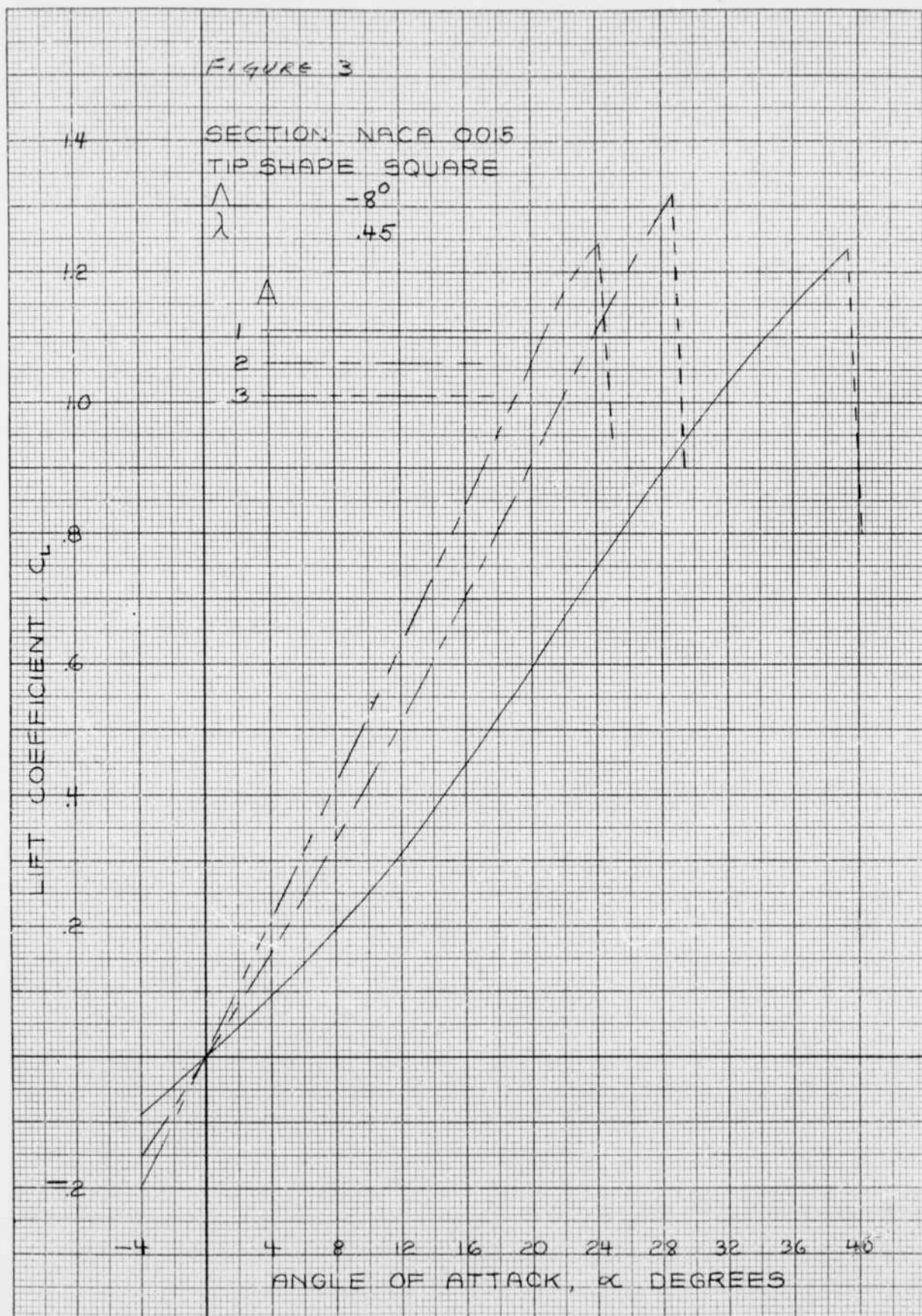


FIGURE 3A

SECTION NACA0015
TIP SHAPE SQUARE
 Λ° — 8
 λ .45

A

1 —————
2 - - - - -
3 - - - - -

6

5

4

3

2

1

DRAG COEFFICIENT, C_D

-4

4

8

12

16

20

24

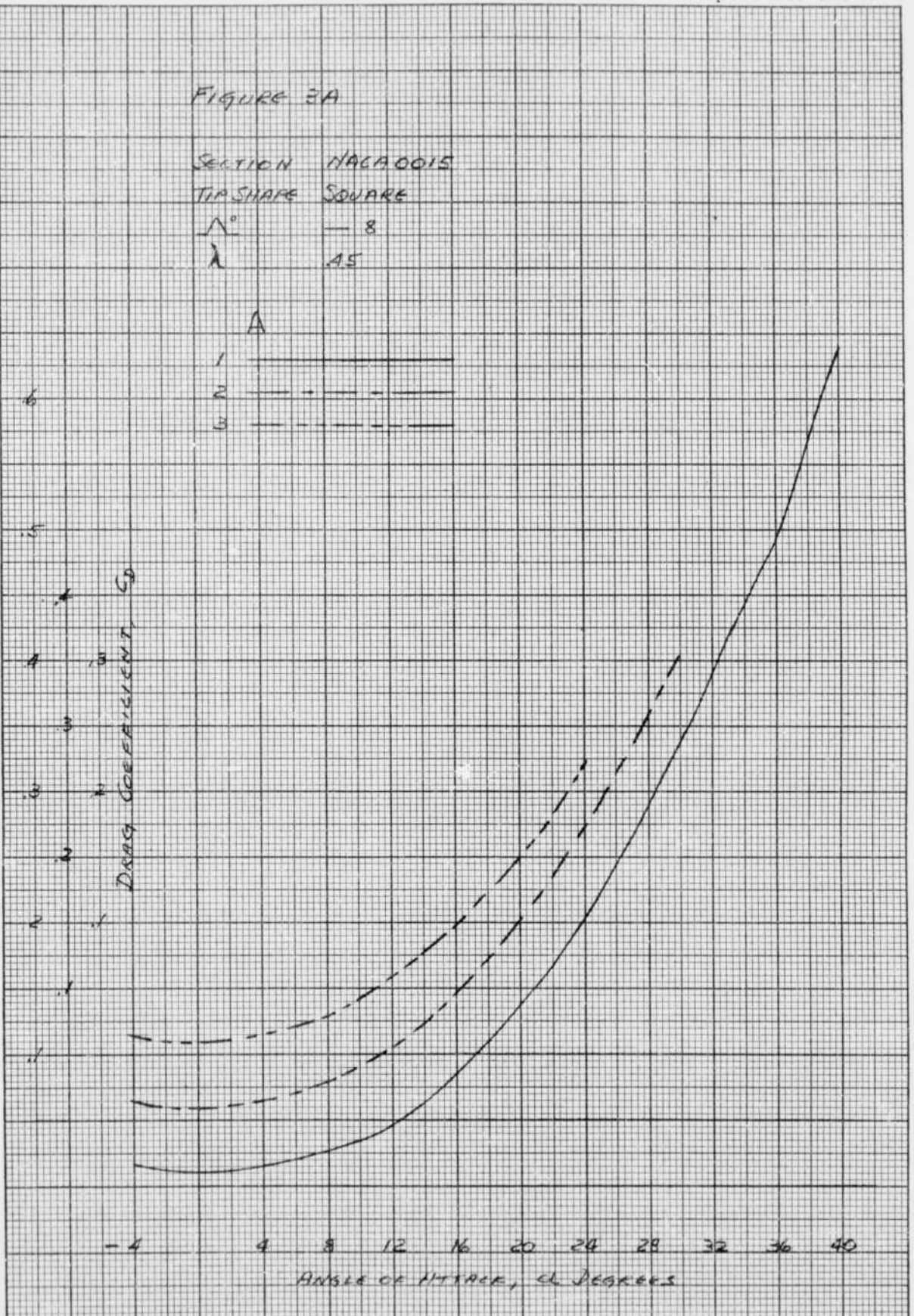
28

32

36

40

ANGLE OF ATTACK, α DEGREES



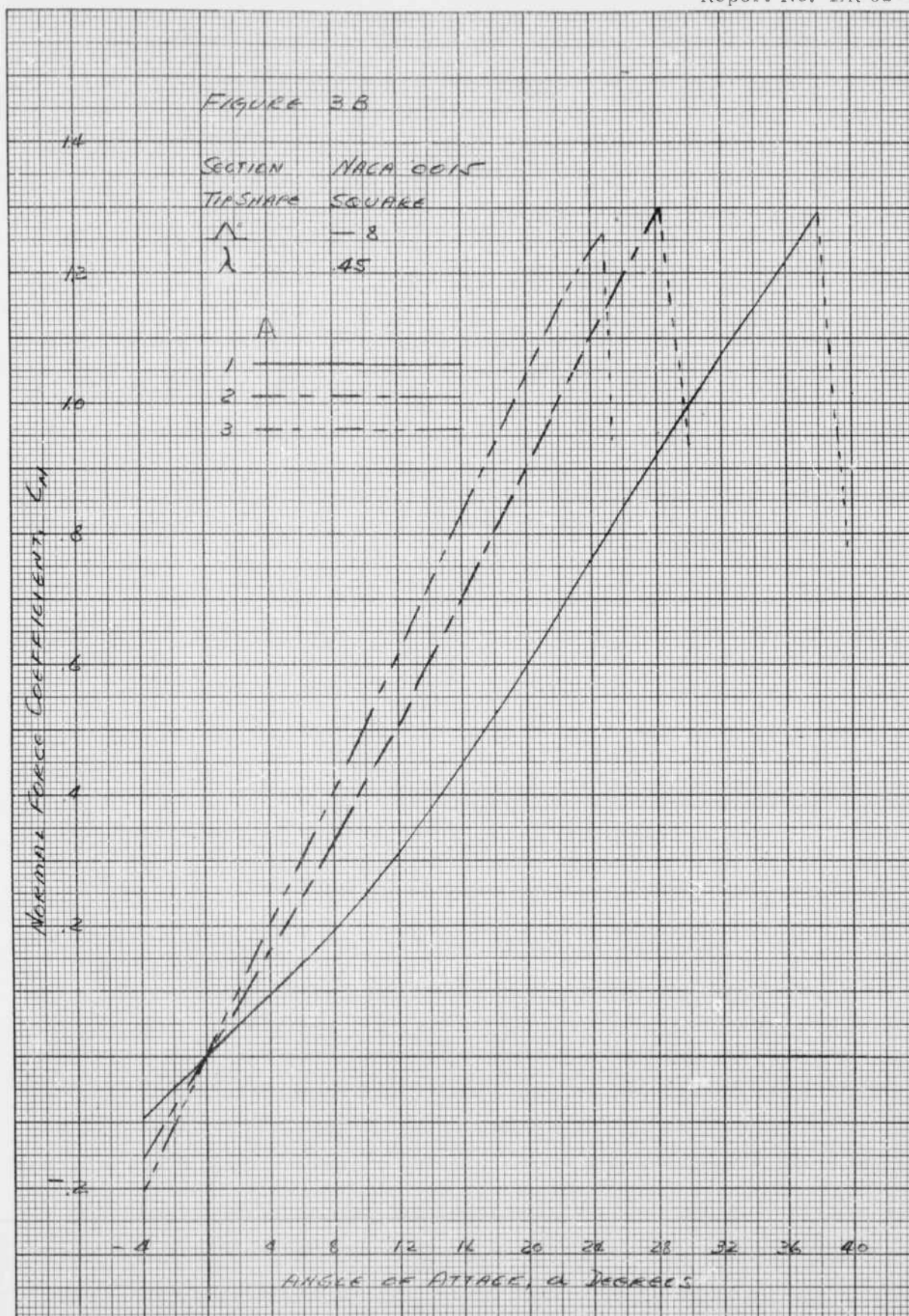


FIGURE 30

SECTION	NACA 0015
TIP SHAPE	SQUARE
Λ	8
λ	45

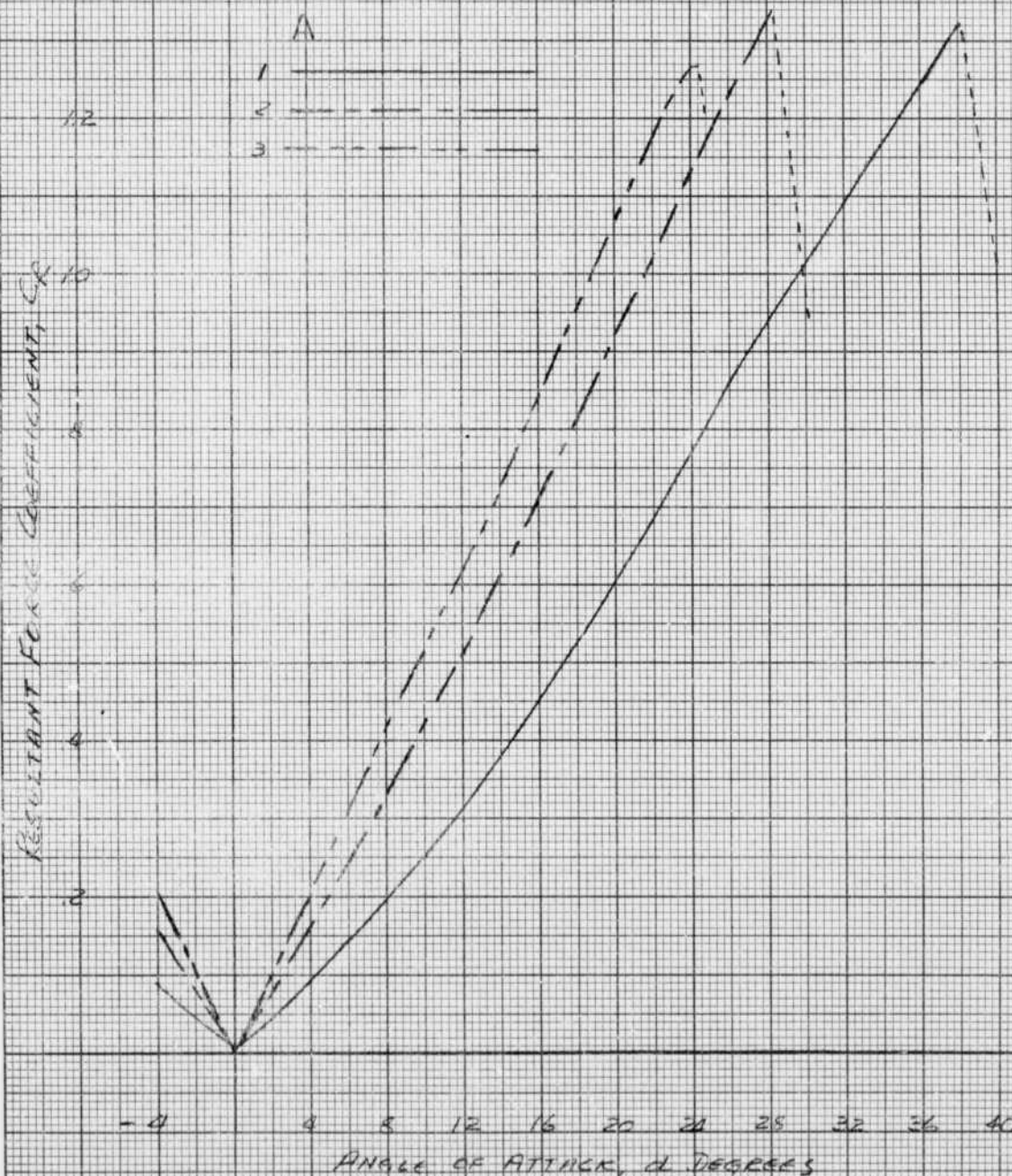
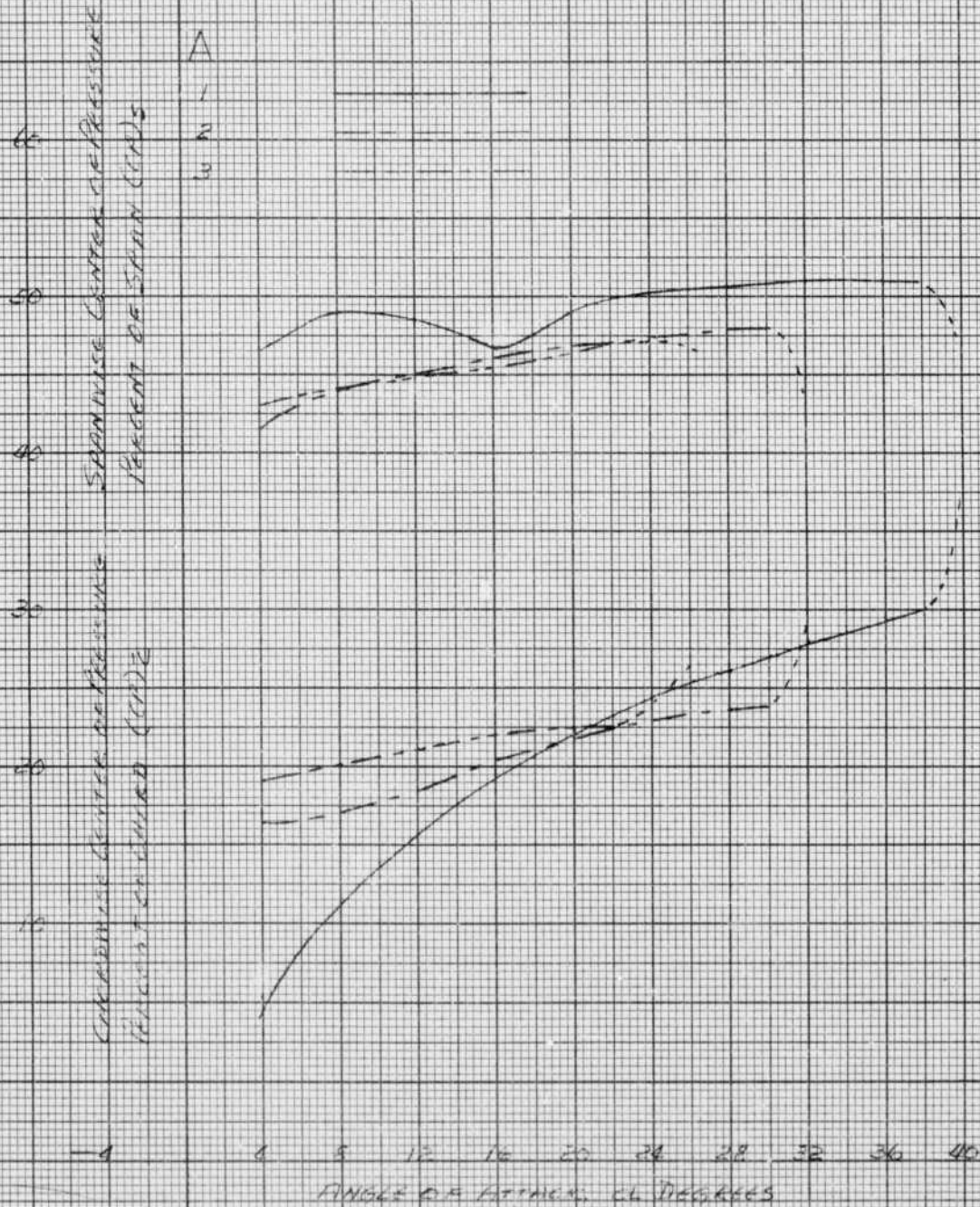


FIGURE 3D

SECTION	NACA 0015
TIP SHAPE	SQUARE
Δ	-5
λ	.45



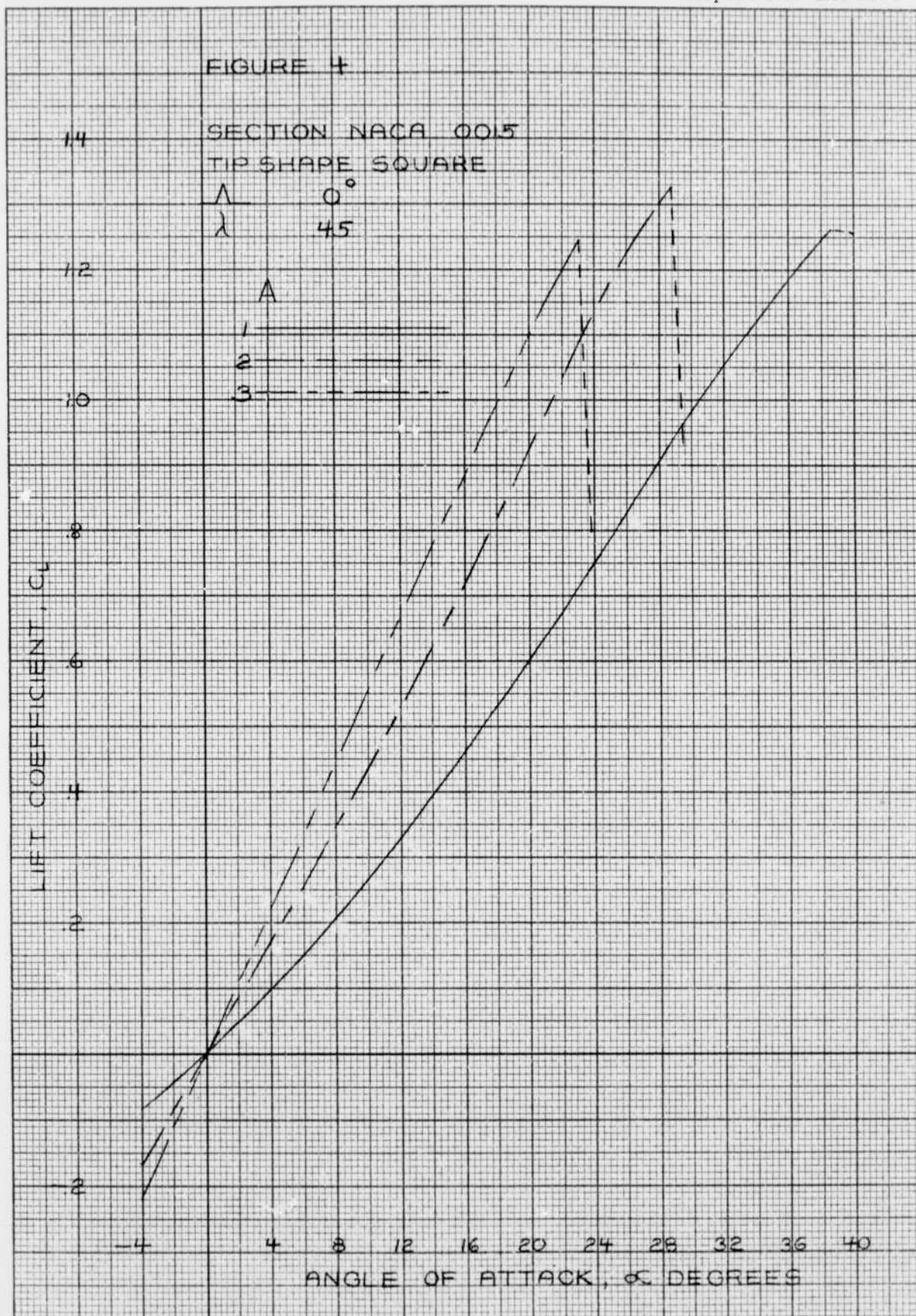


FIGURE 4A

SECTION NACA 0015

TIP SHAPE SQUARE

λ° 0
 λ .45

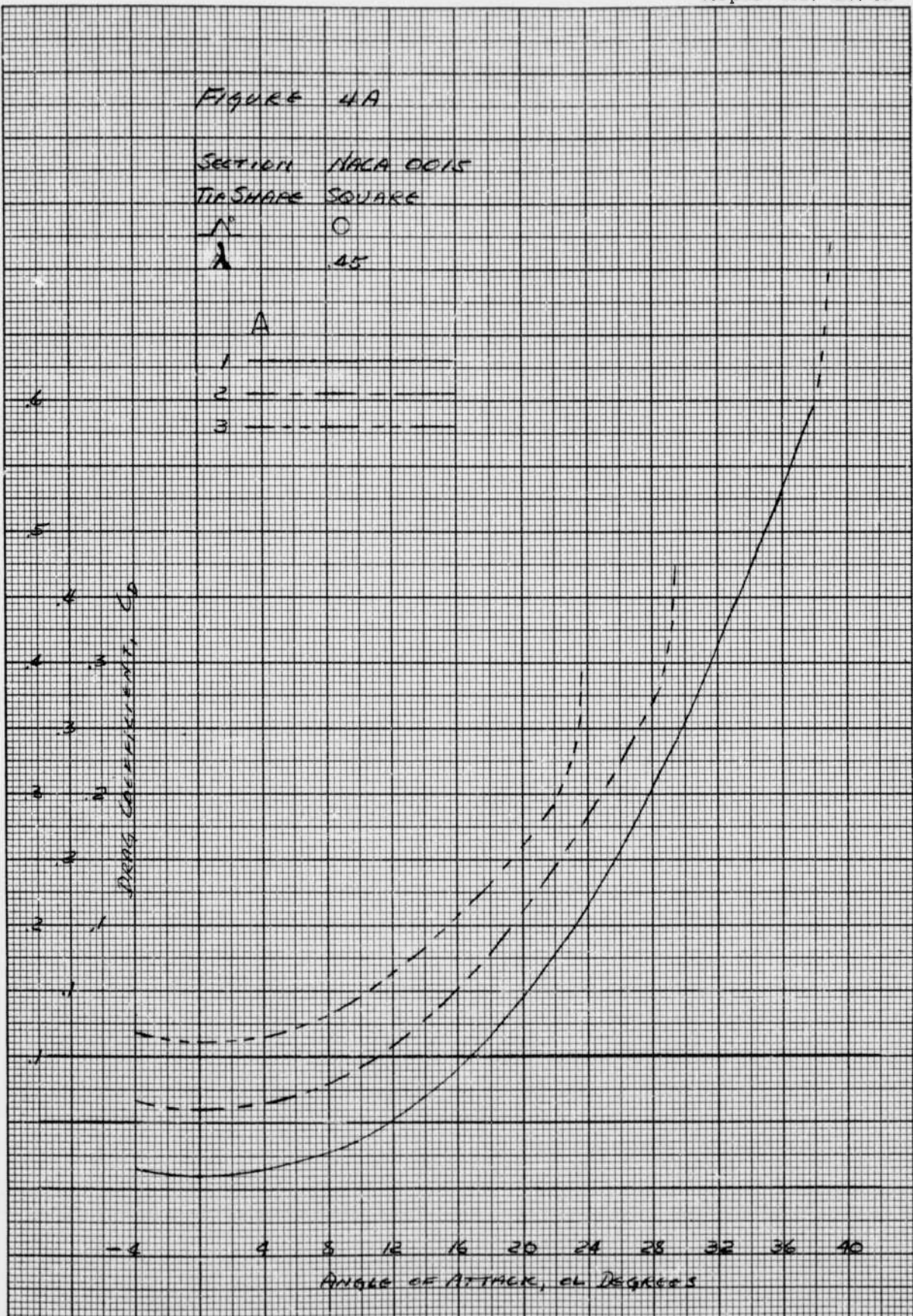
A

1 —————
2 - - - - -
3 - - - - -

DRAG COEFFICIENT, C_D

-4 4 8 12 16 20 24 28 32 36 40

ANGLE OF ATTACK, α , DEGREES



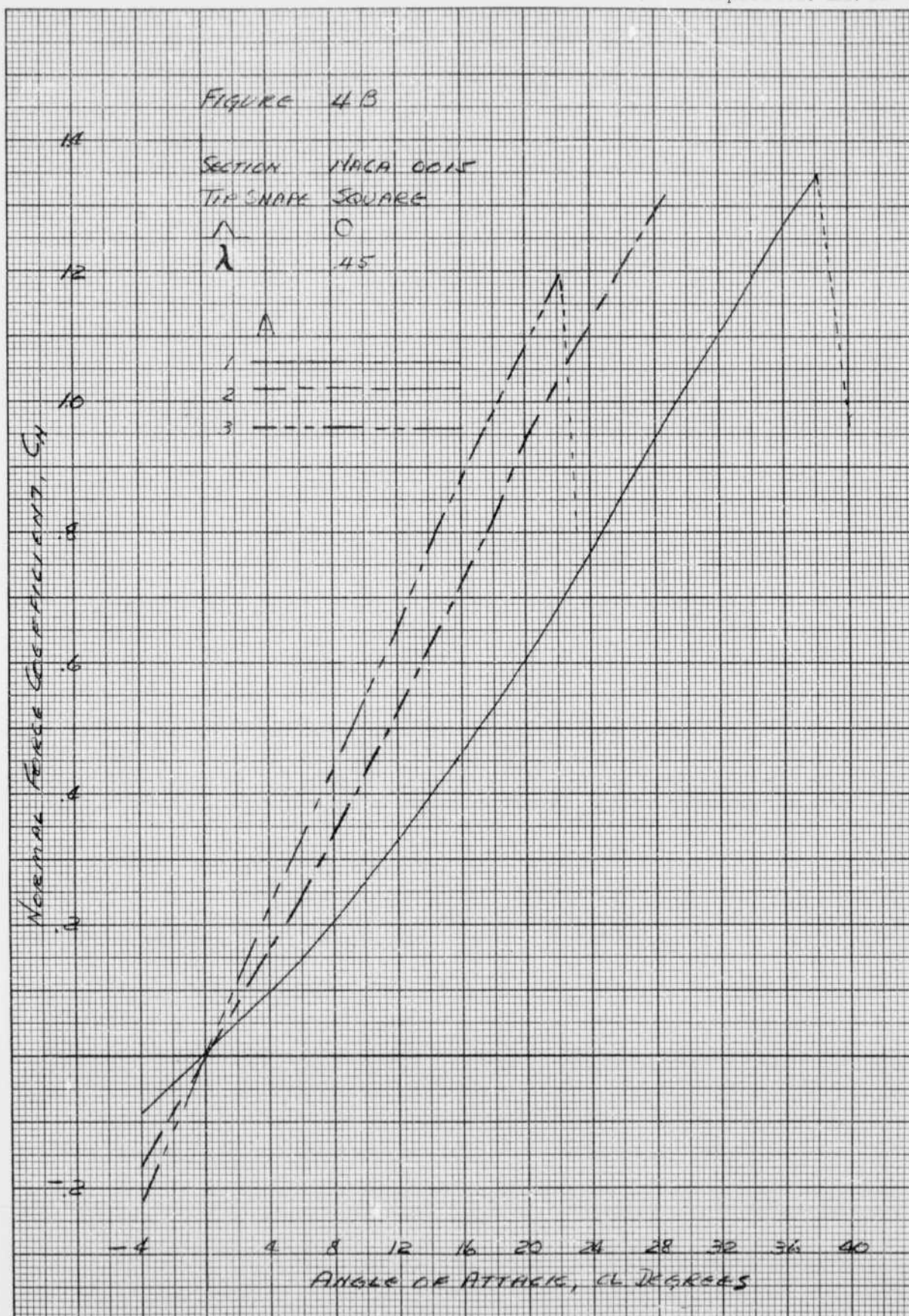


FIGURE 4C

SECTION NACA 0015

TIP SHAPE SQUARE

Λ 0
 λ 45

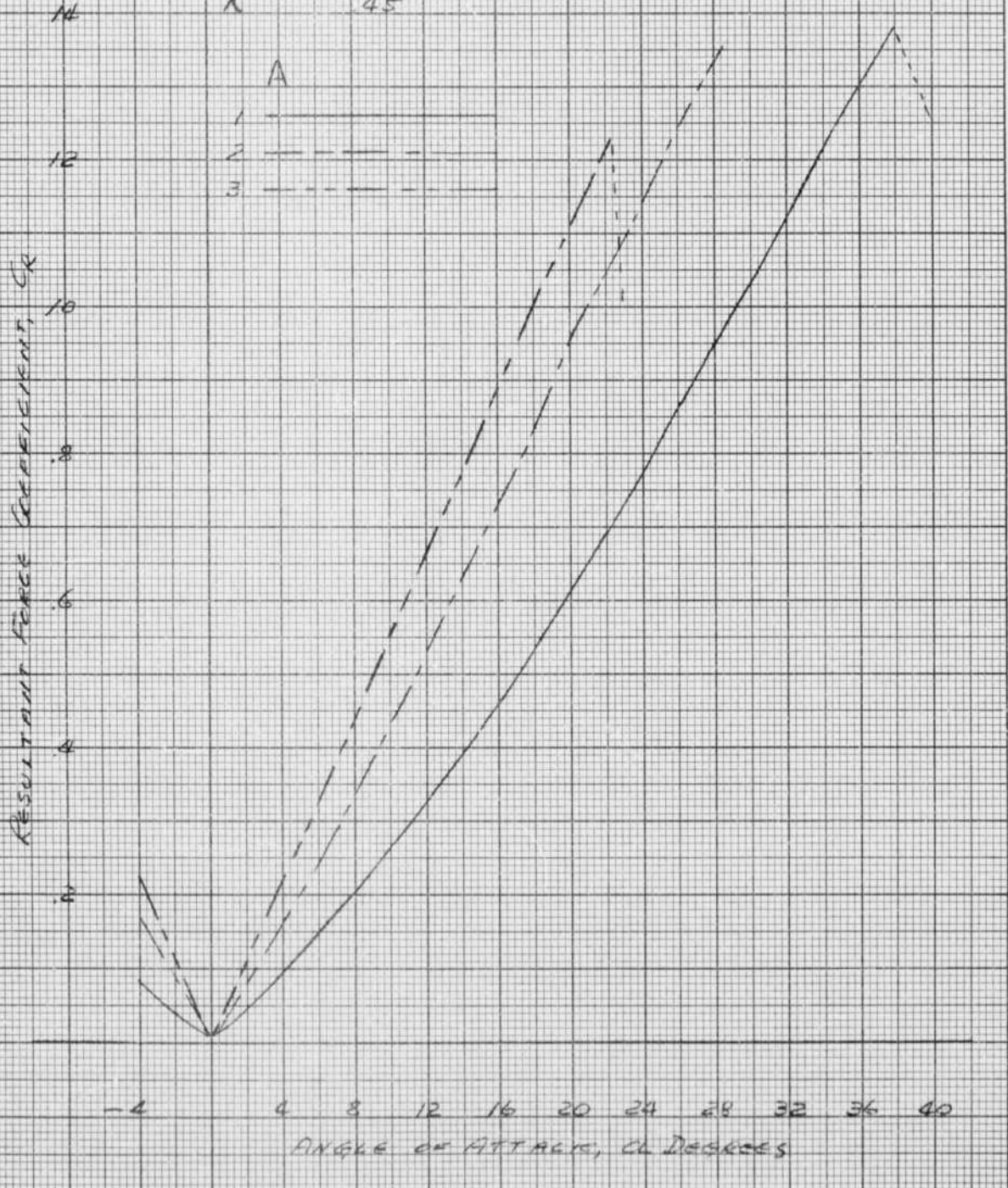


FIGURE 4D

SECTION	AREA OUT TIPS IN IN	SQUARE
A	0	
1	45	

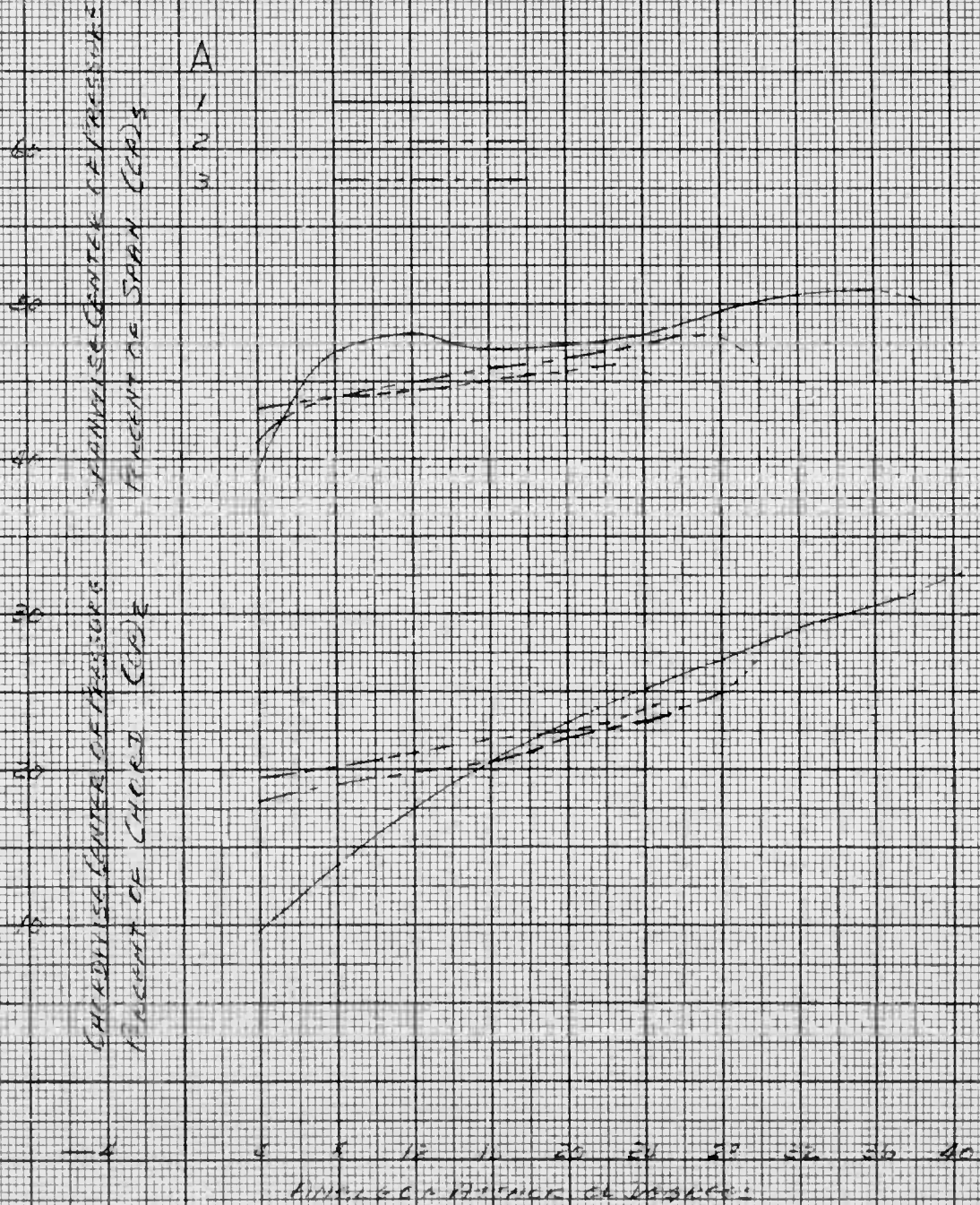


FIGURE 5

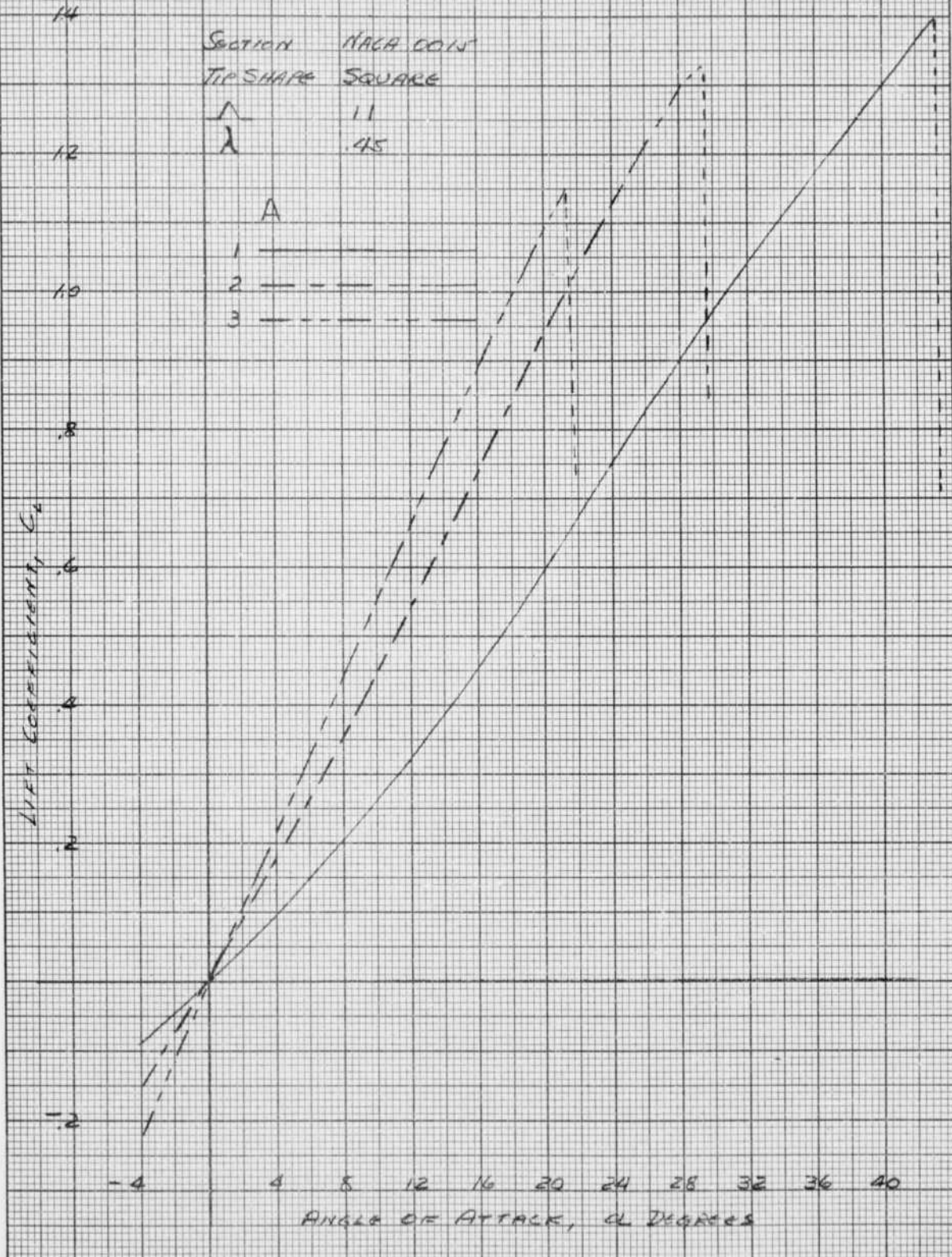


FIGURE 5A

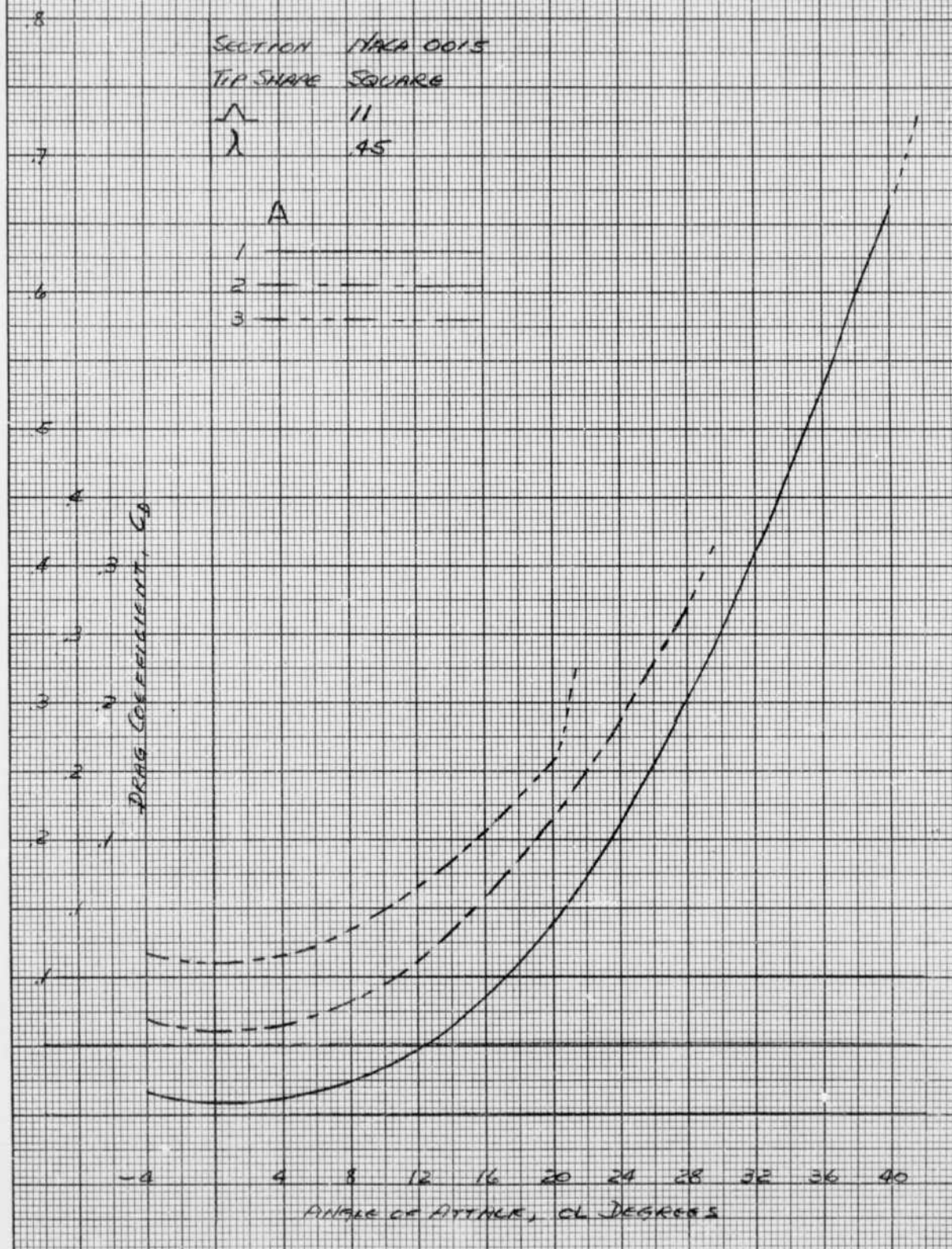


FIGURE 5B

SECTION NACA 0015

TIP SHAPE SQUARE

Λ 11
 λ .45

A

- 1 —————
- 2 - - - - -
- 3 - - - - -

NORMAL FORCE COEFFICIENT, C_N

14

12

10

8

6

4

2

-2

-4

4

8

12

16

20

24

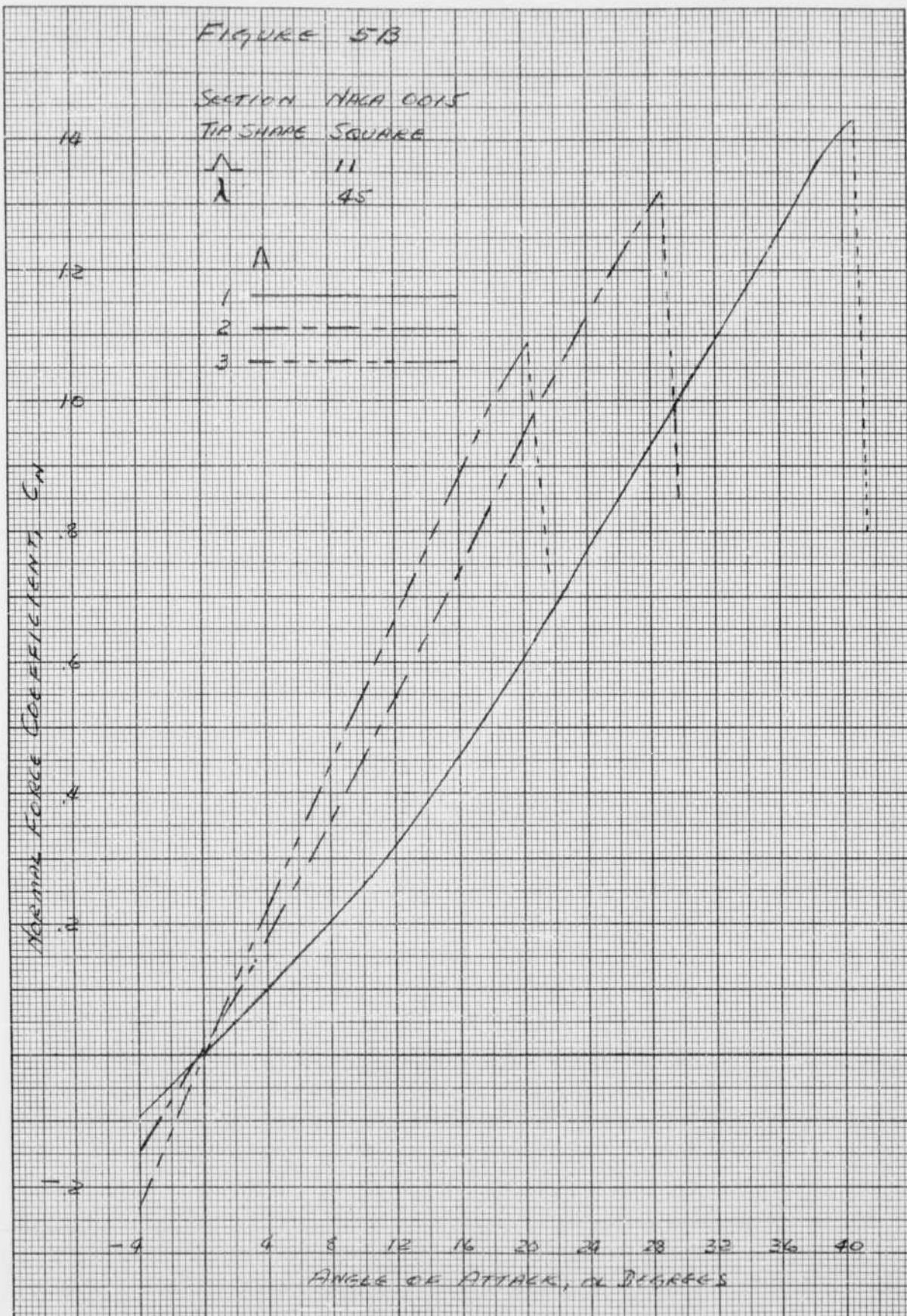
28

32

36

40

ANGLE OF ATTACK, α DEGREES



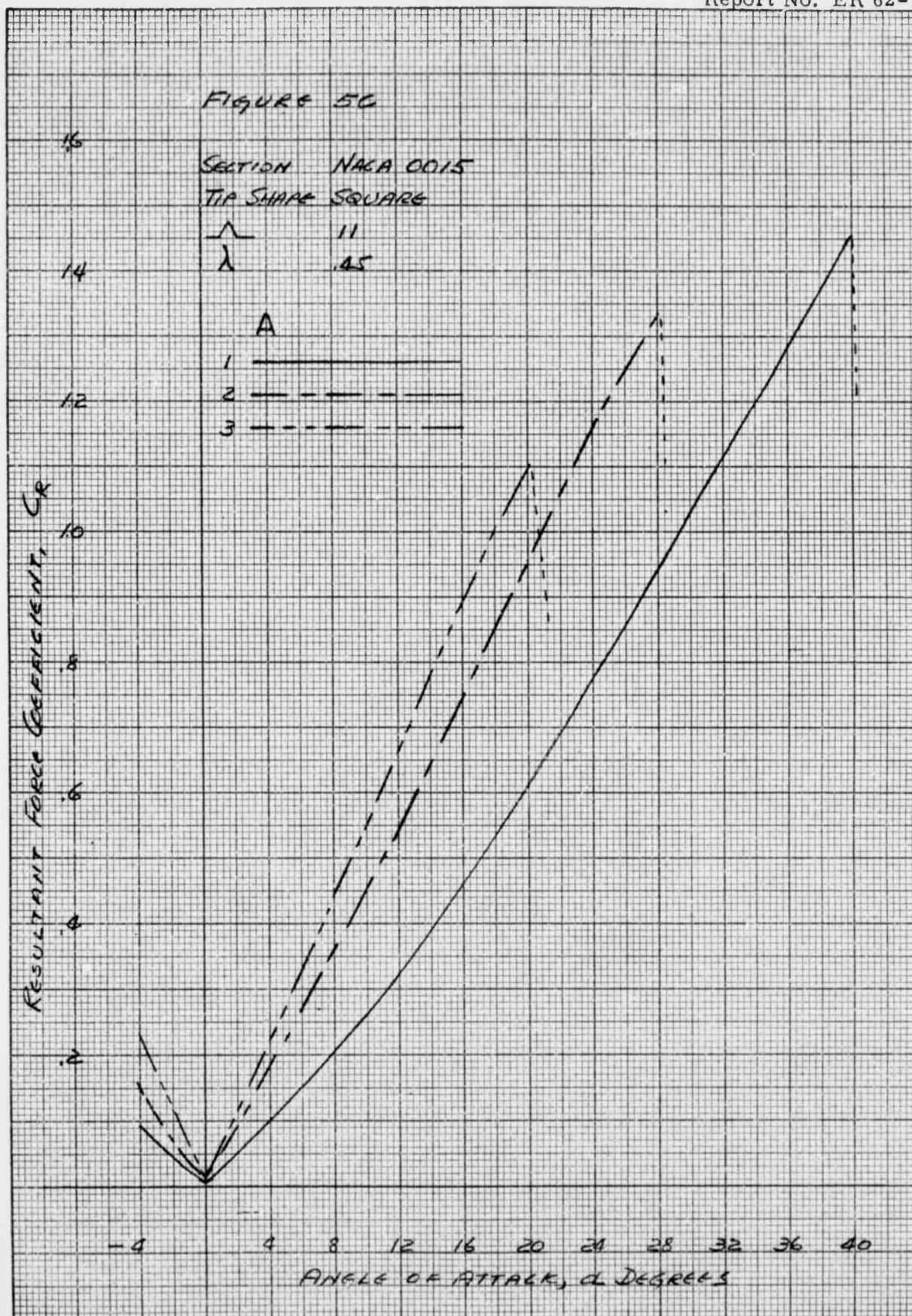
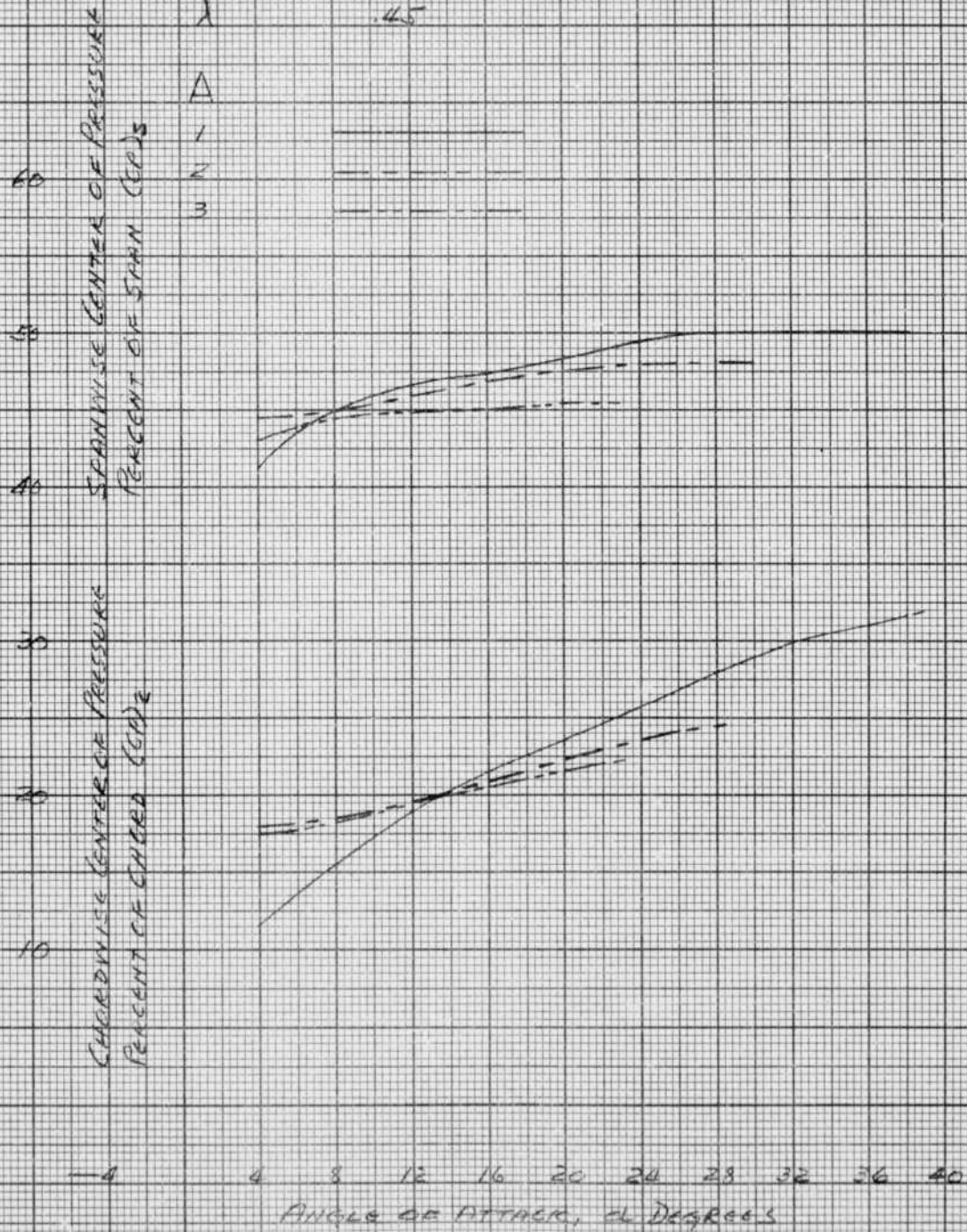


FIGURE 5D

SECTION	NACA 6615
TIP SHAPE	SQUARE
Δ	11
λ	.45



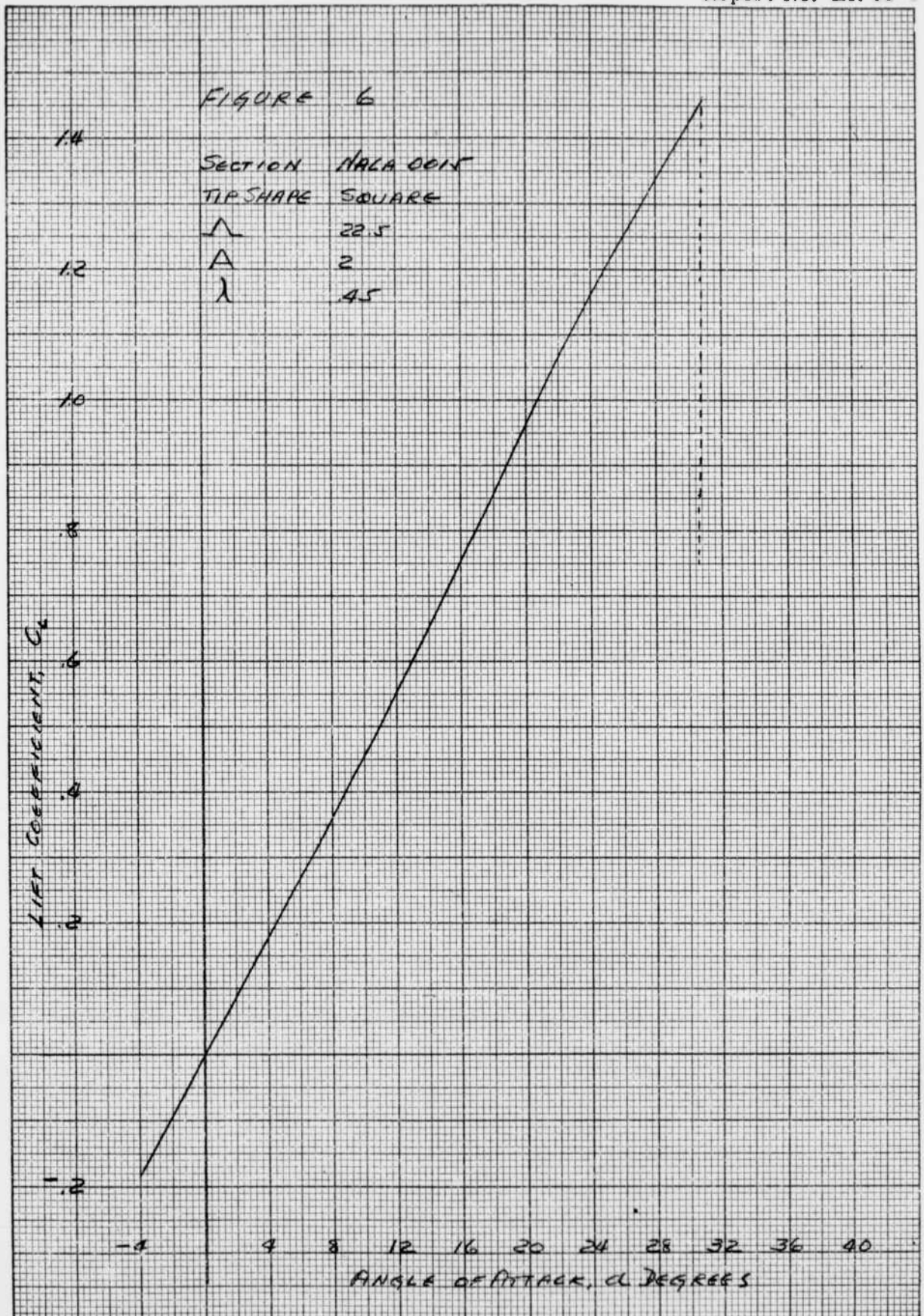
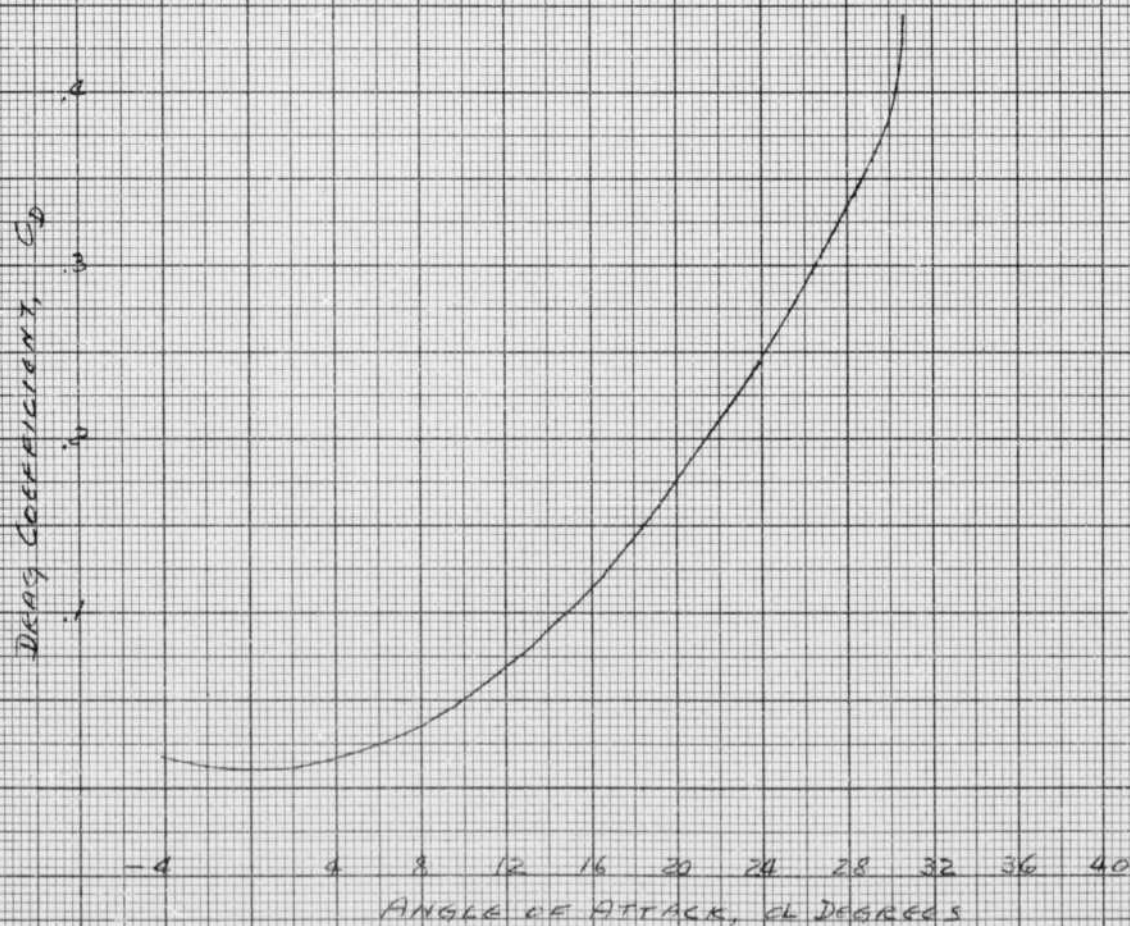
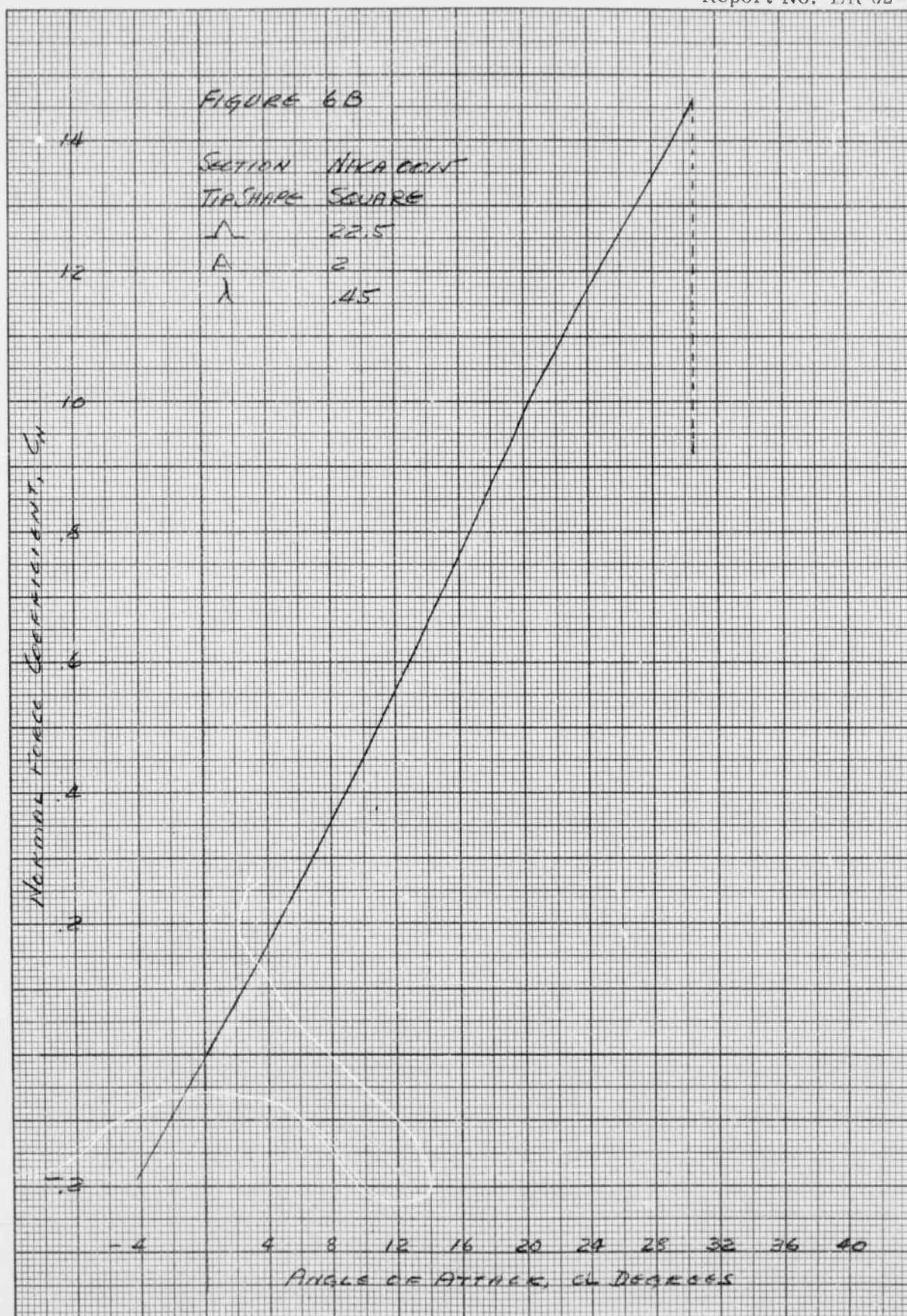


FIGURE 6A

SECTION	MACH 0.15
TIP SHAPE	SQUARE
Λ	22.5
A	2
λ	.45





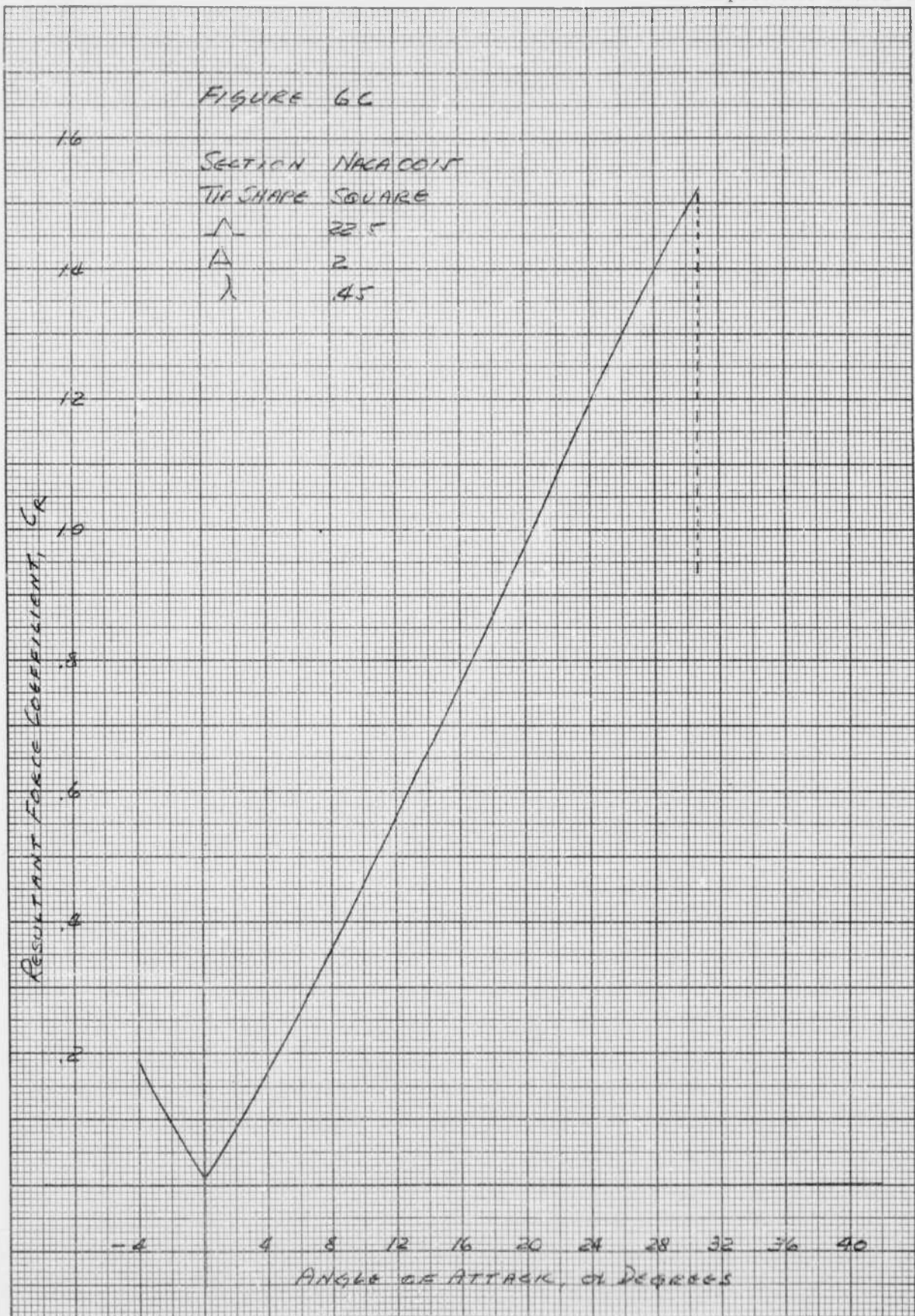
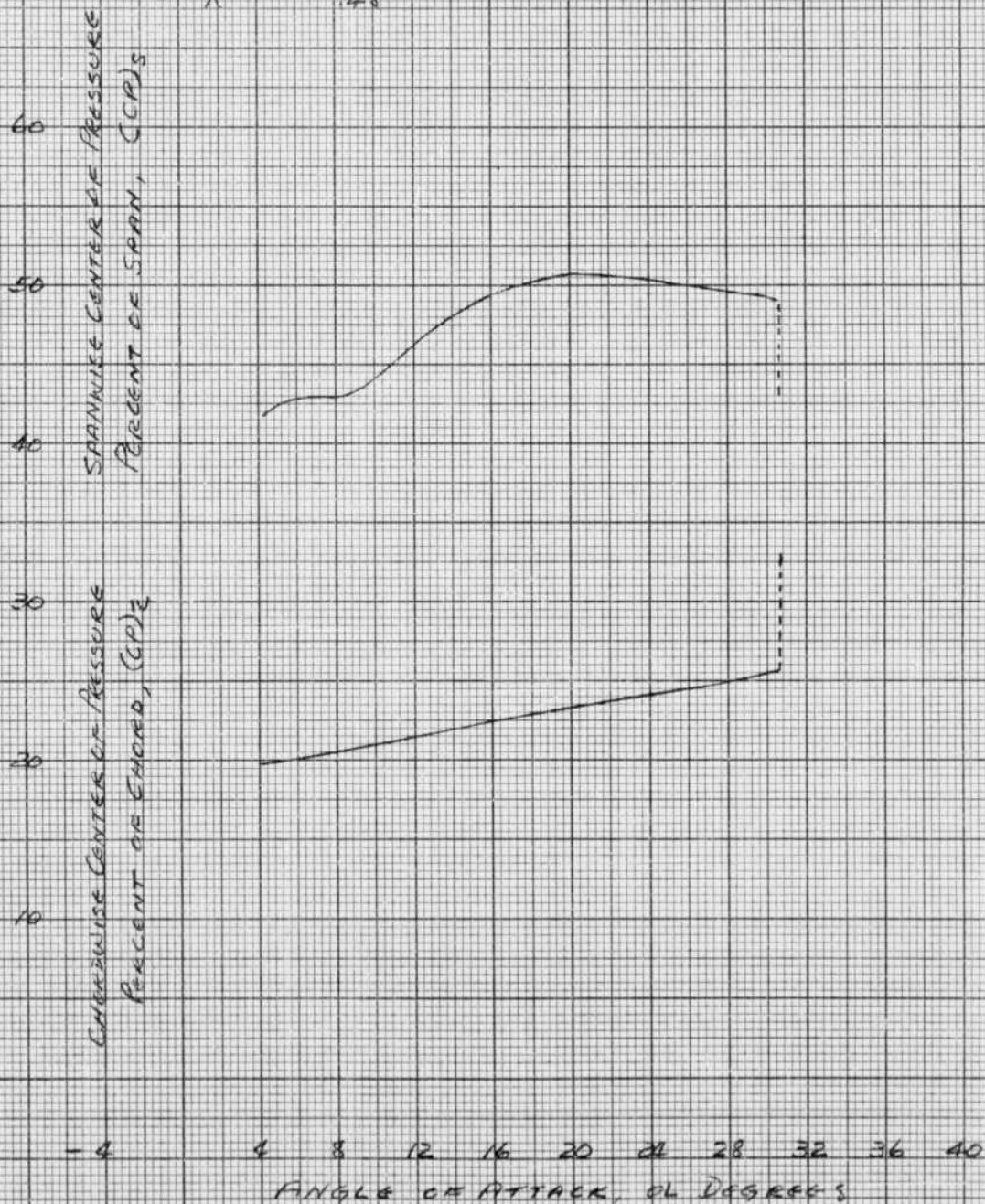


FIGURE 6D

SECTION NACA 0015
TIP SHAPE SQUARE
 Λ 22.5
A 2
 λ .45



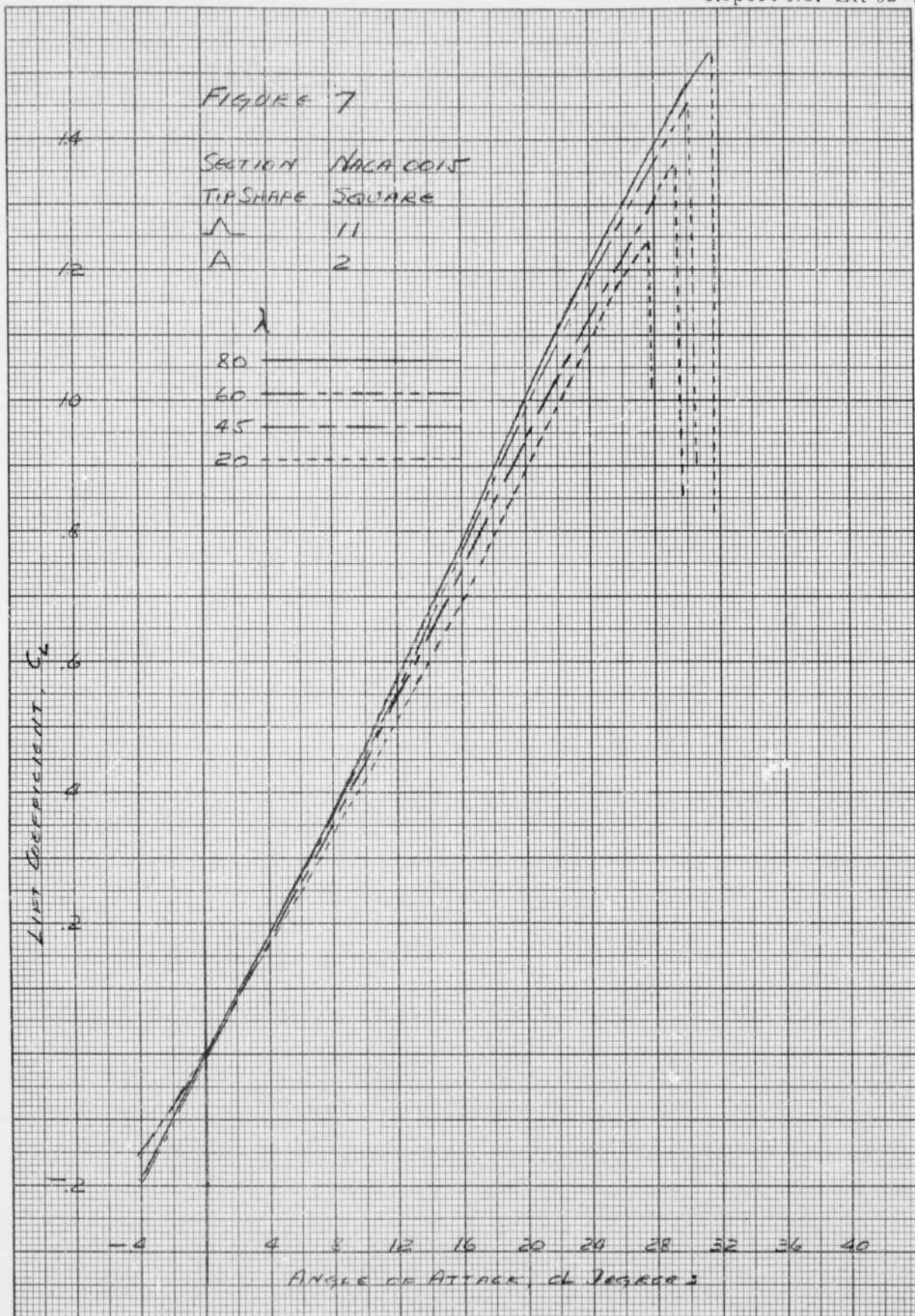


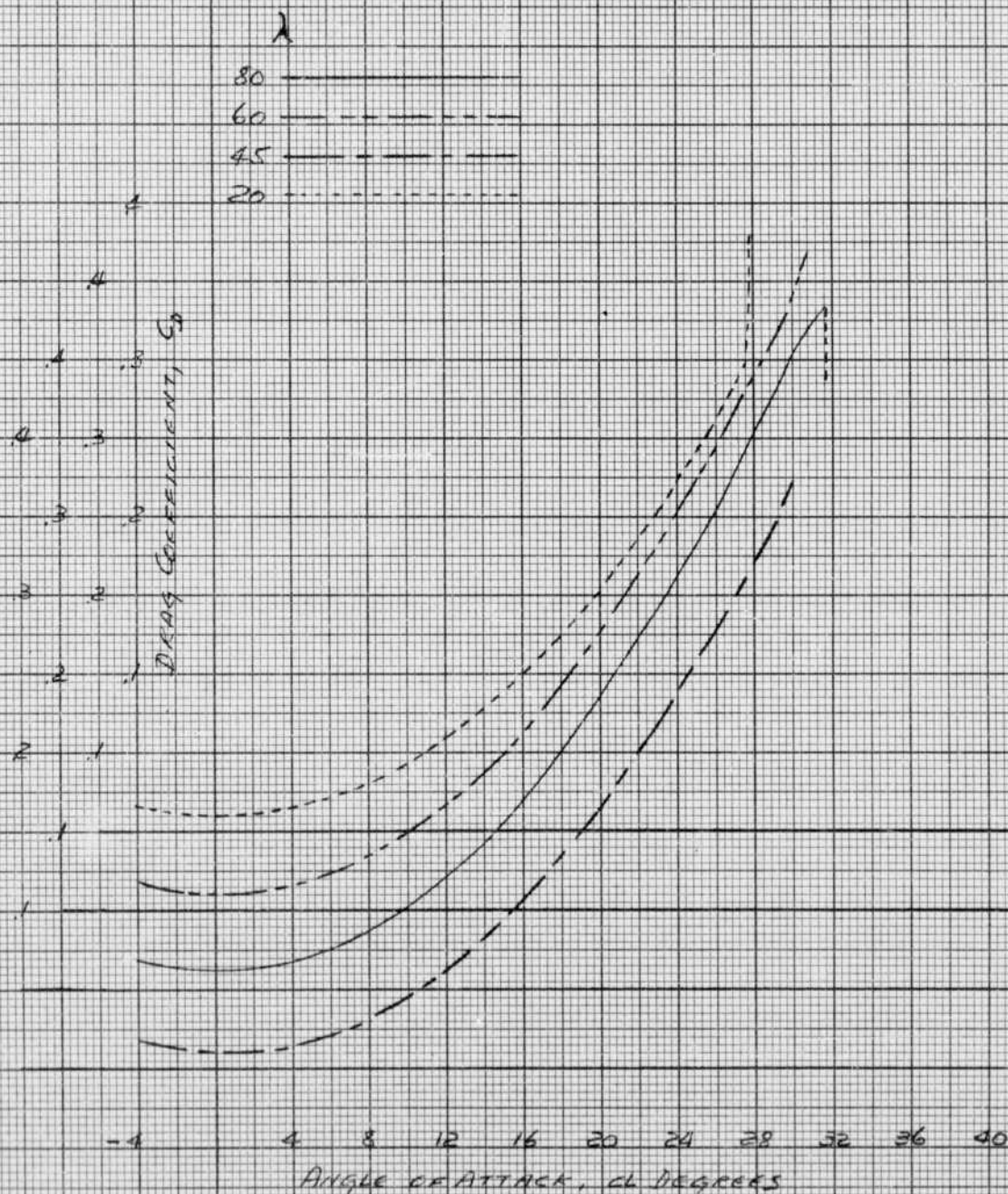
FIGURE 7A

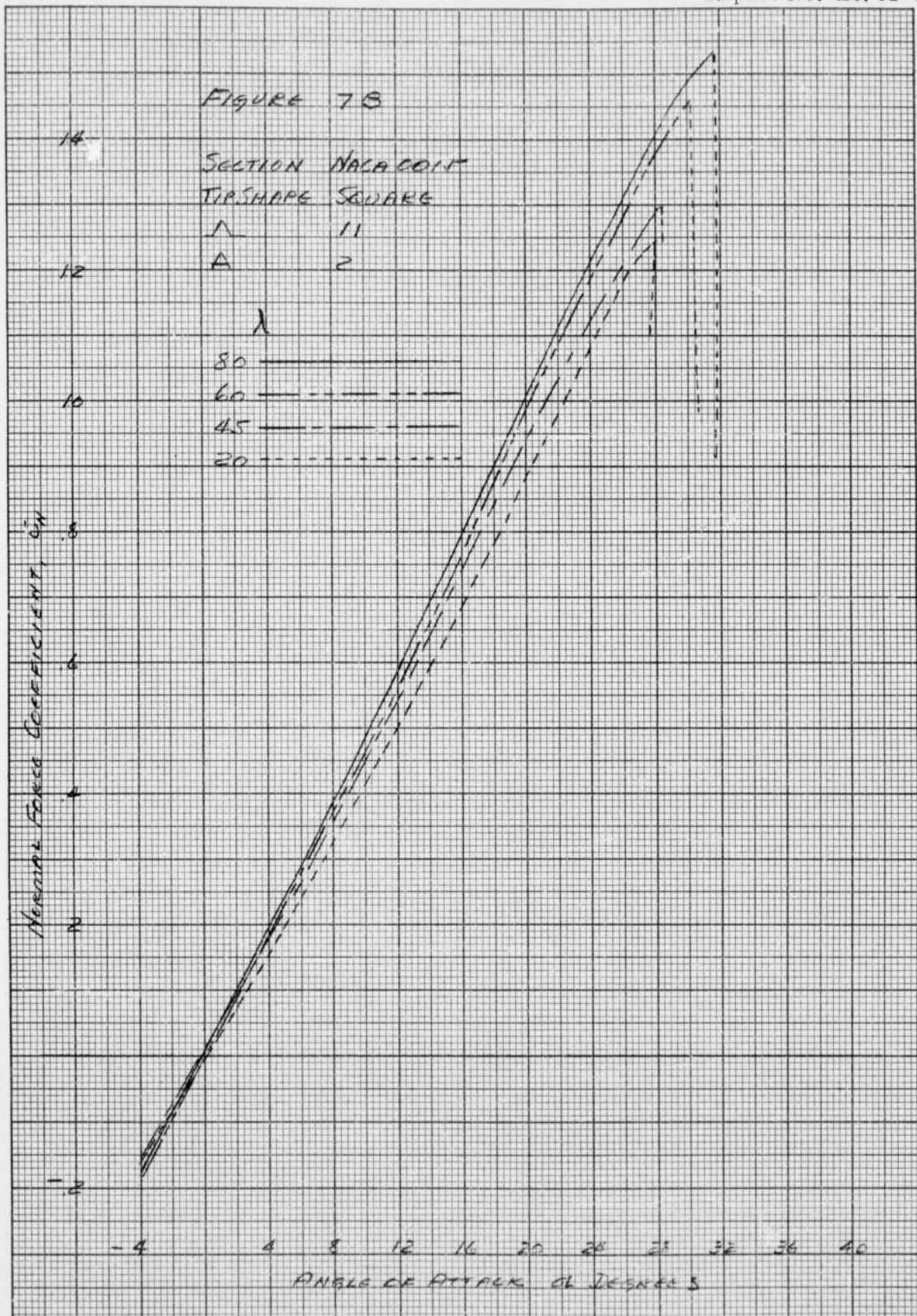
SECTION NACA 0015

TIP SHAPE SQUARE

λ 11

A 2





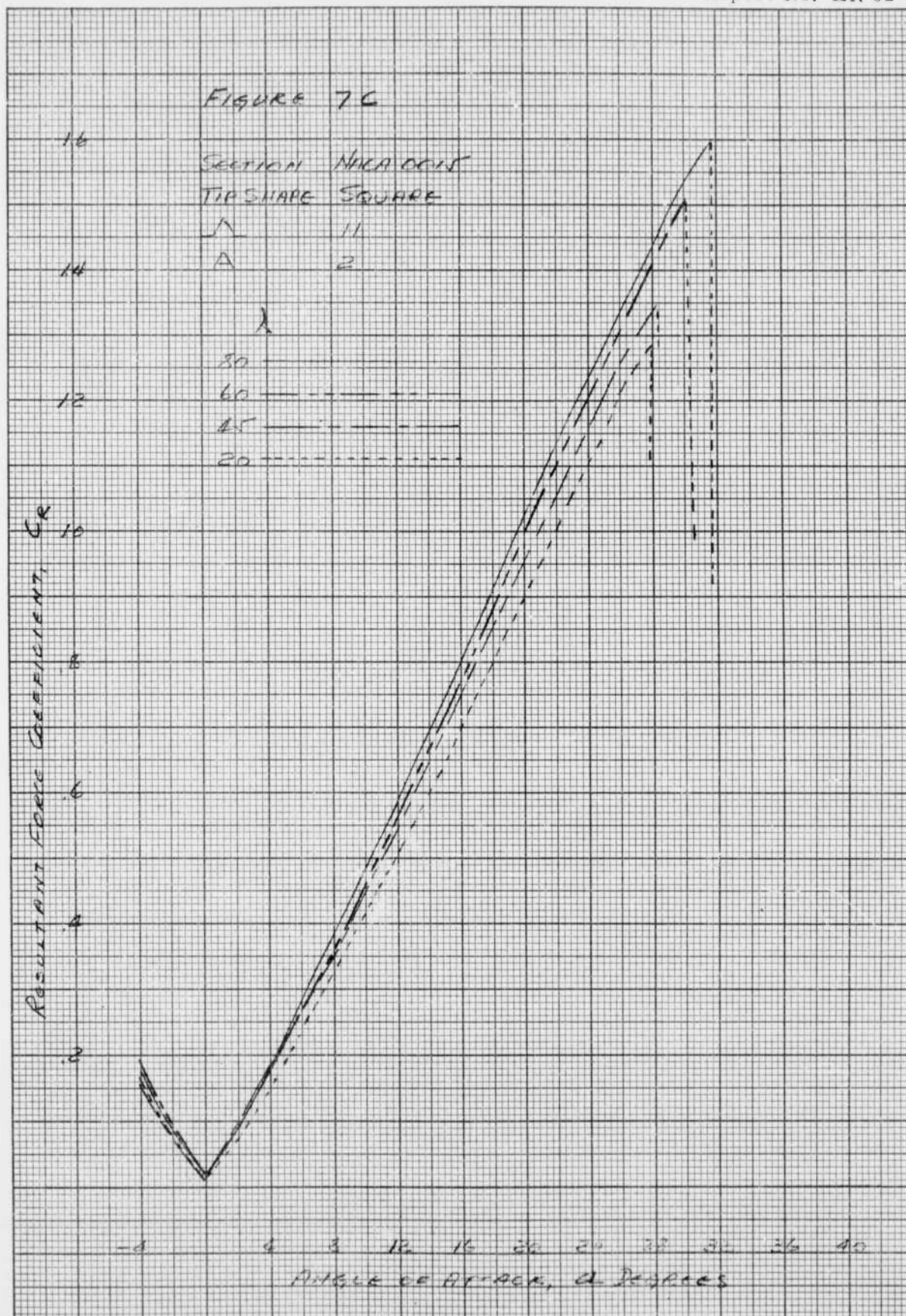


FIGURE 7D

SECTION NACA 0015
TIP SHAPE SQUARE

λ 11
A 2

λ
80
60
45
20

SPANWISE CENTER OF PRESSURE
PERCENT OF SPAN (CP)₁

CHORDWISE CENTER OF PRESSURE
PERCENT OF CHORD (CP)₂

-4

4 8 12 16 20 24 28 32 36 40

ANGLE OF ATTACK, α , DEGREES

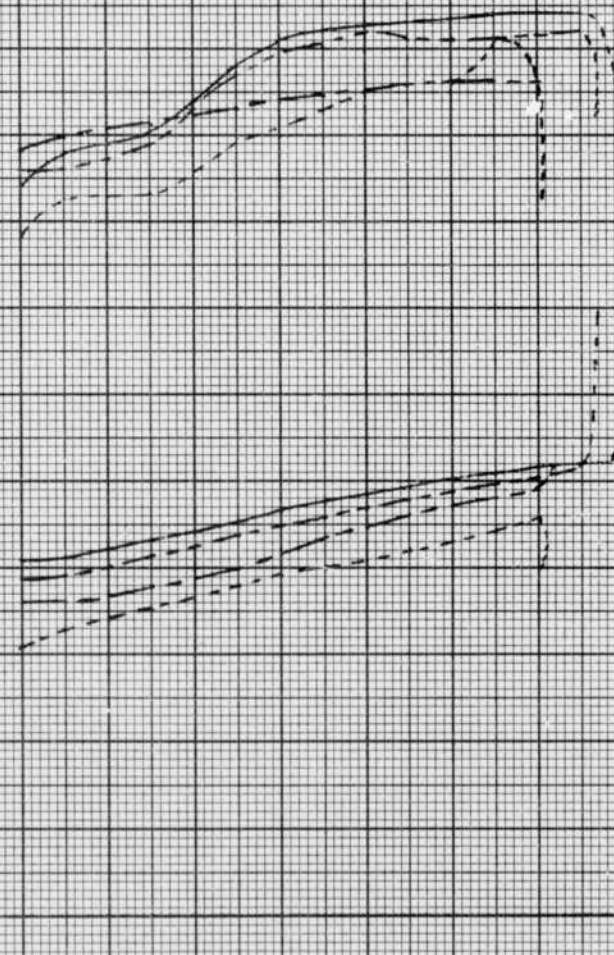


FIGURE 8

SECTION	NACA 0015
TIP SHAPE	SQUARE
Λ	0
λ	10

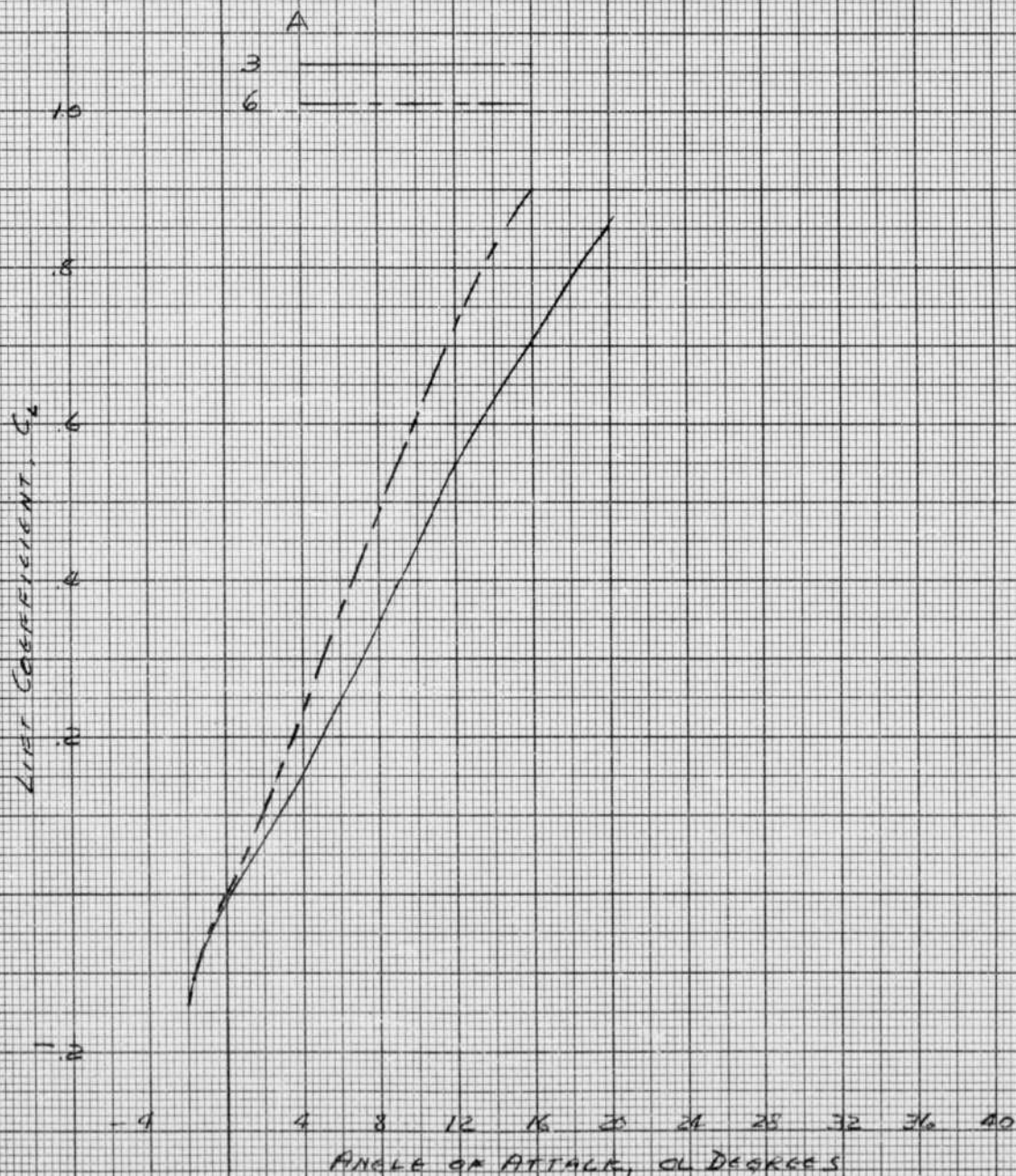


FIGURE 8A

SECTION NACA 0012

TIP SHAPE SQUARE

λ 0
 λ 1.0

A

3 —————
6 - - - - -

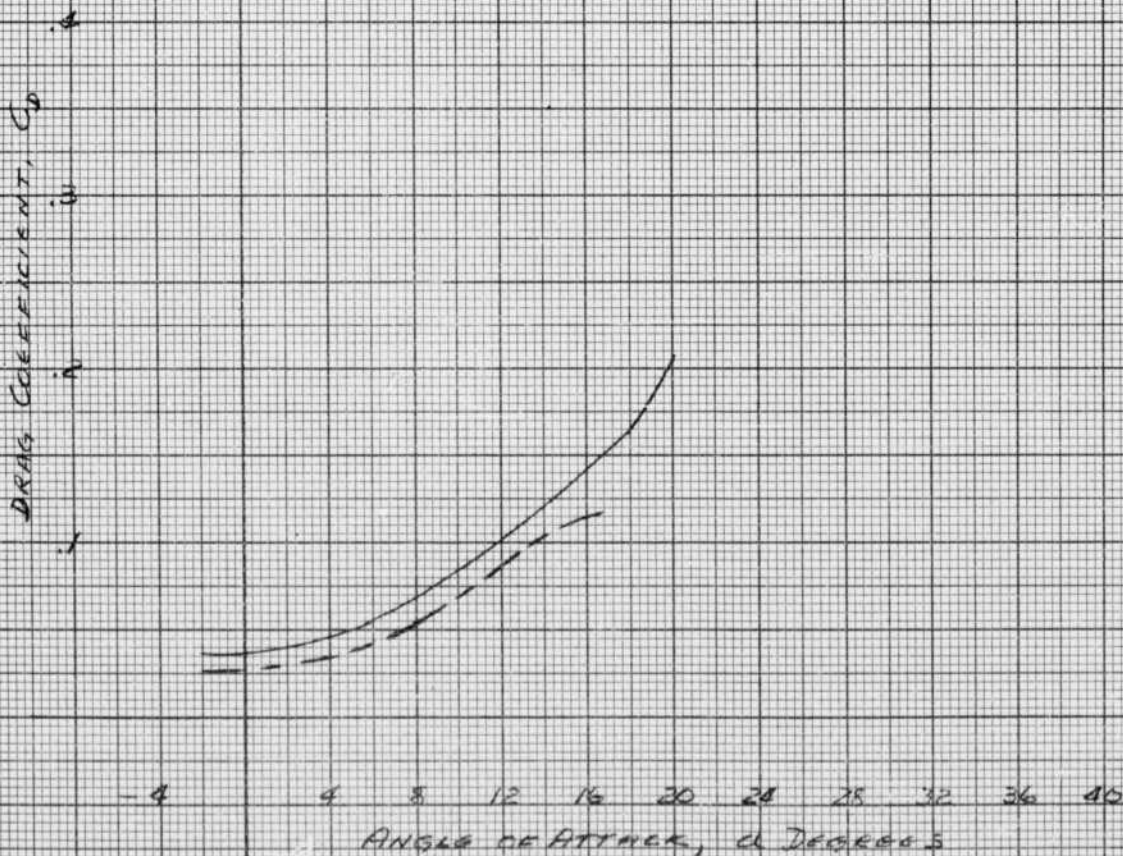


FIGURE 8B

SECTION NACA 0015
TIP SHAPE SQUARE

λ 0
 λ 1.0

A

3 —————
6 - - - - -

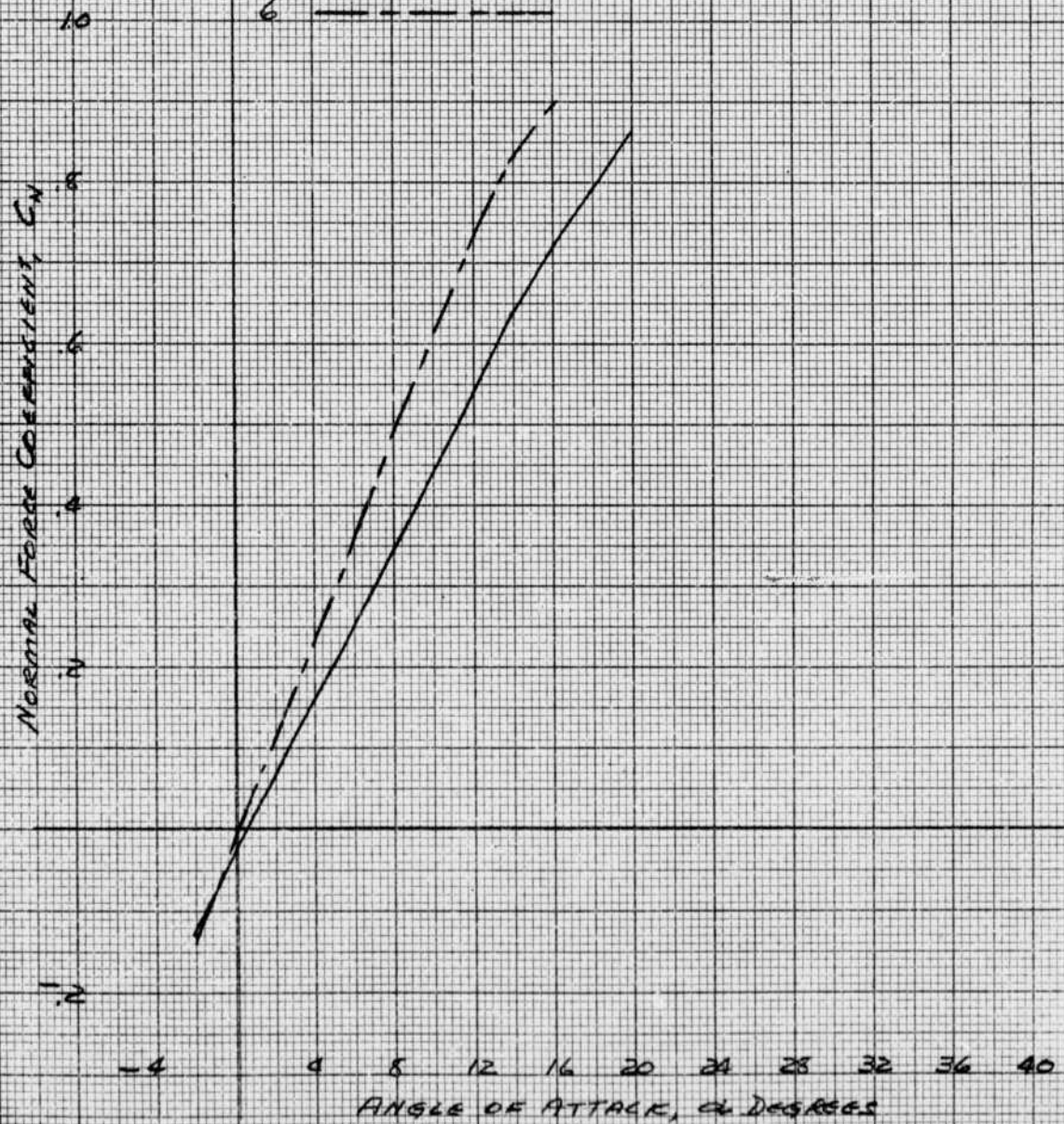


FIGURE 86

SECTION NACA 0012
TIP SHAPE SQUARE

Λ 0
 λ 1.0

A
3 —————
6 - - - - -

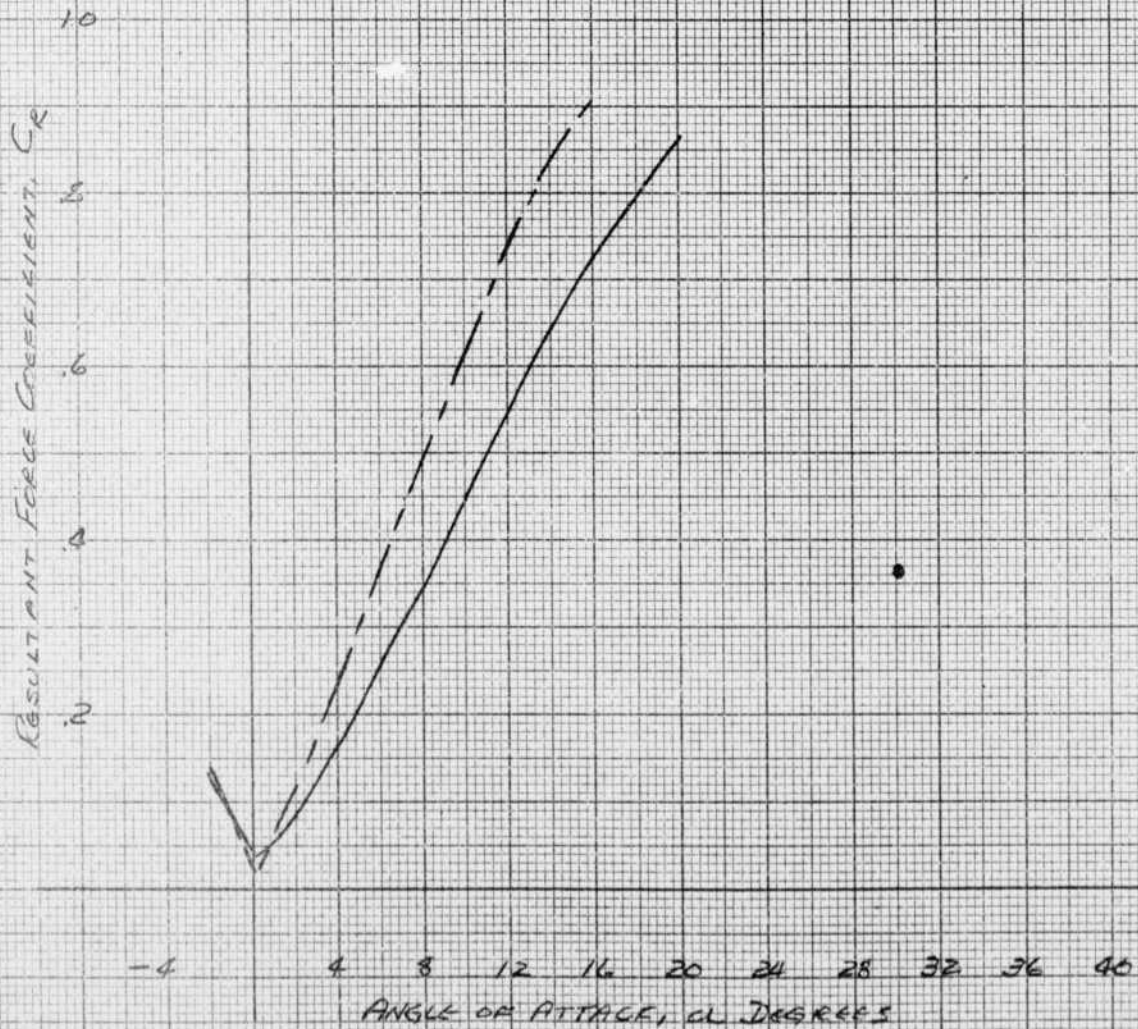


FIGURE 8D

SECTION	NACA 0015
TIP SHAPE	SQUARE
λ	0
λ	1.0

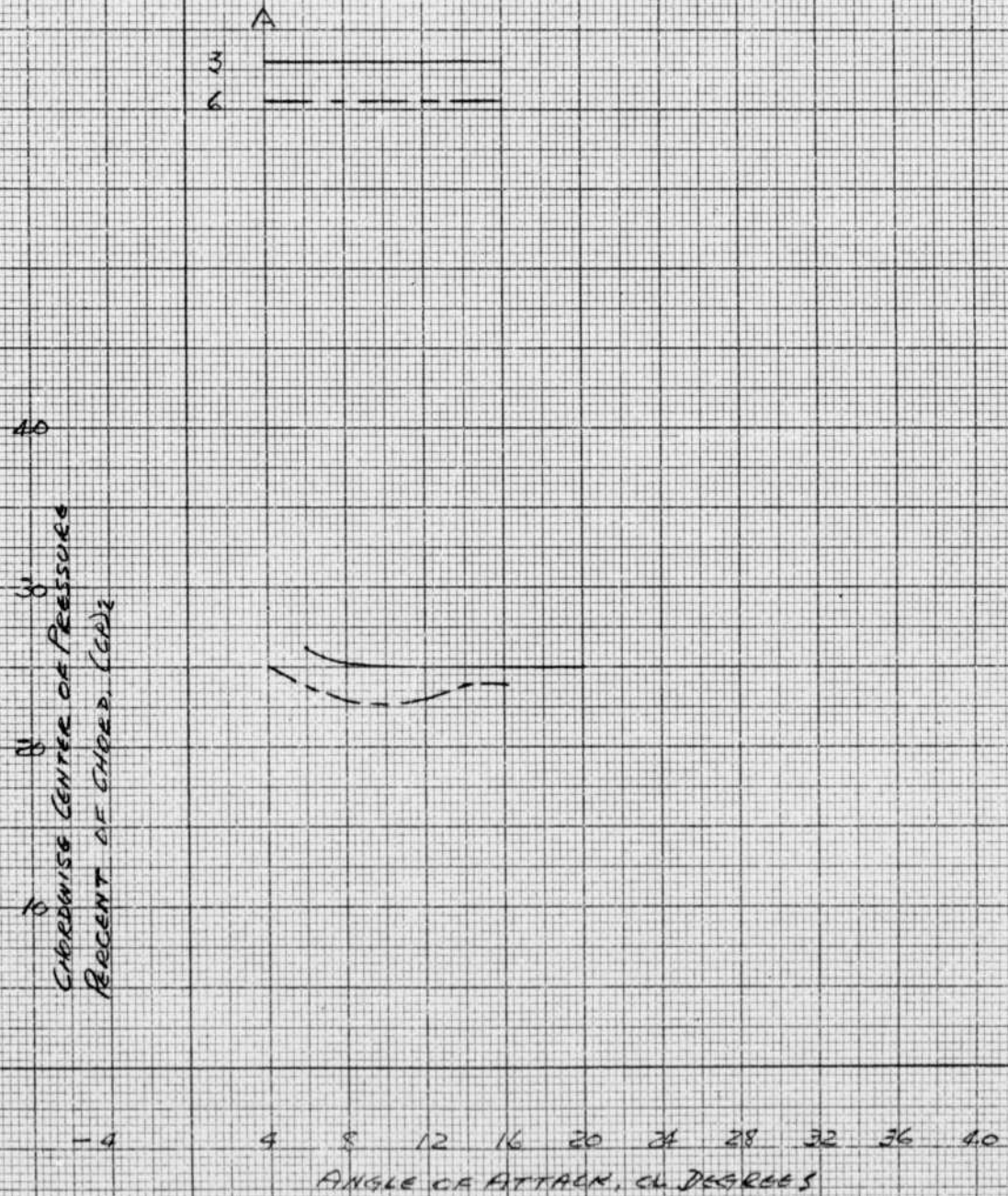


FIGURE 9

SECTION NACA 0015
TIP SHAPE SQUARE

λ 30
 λ 10

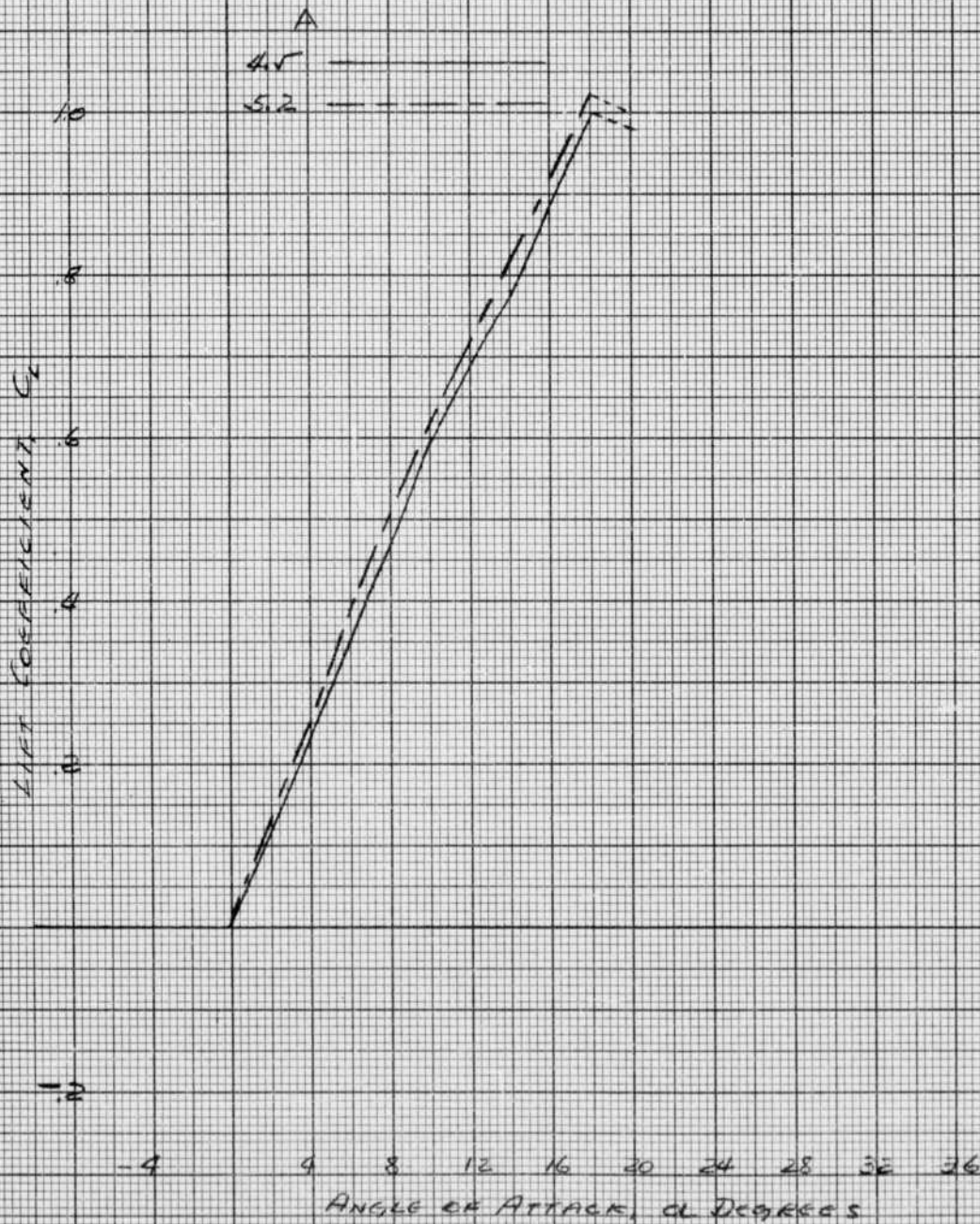


FIGURE 9A

SECTION	NACA 0015
TIP SHAPE	SQUARE
Λ	30
λ	1.0

A	
0.5	—————
5.2	- - - - -

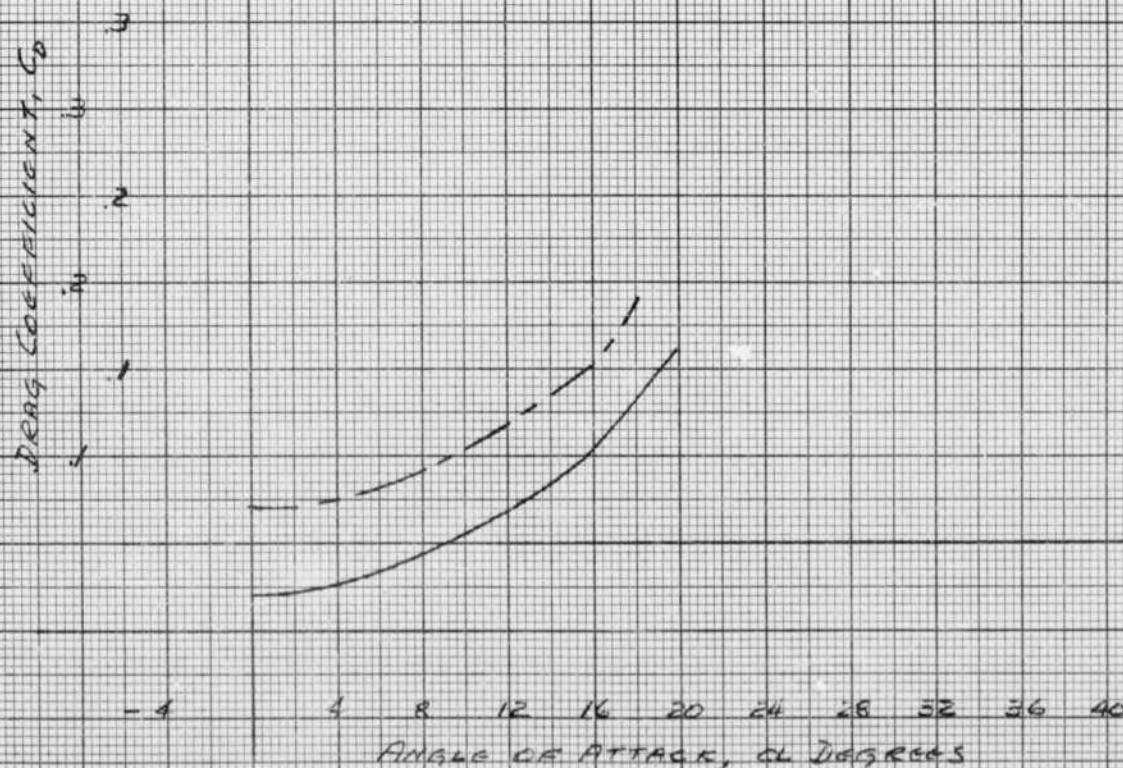


FIGURE 9B

SECTION NACA 0015
TIP SHAPE SQUARE

λ 30
 λ 1.0

A

4.5 —————
5.2 - - - - -

NORMAL FORCE COEFFICIENT, C_N

-2

-4

4

8

12

16

20

24

28

32

36

40

ANGLE OF ATTACK, α , DEGREES

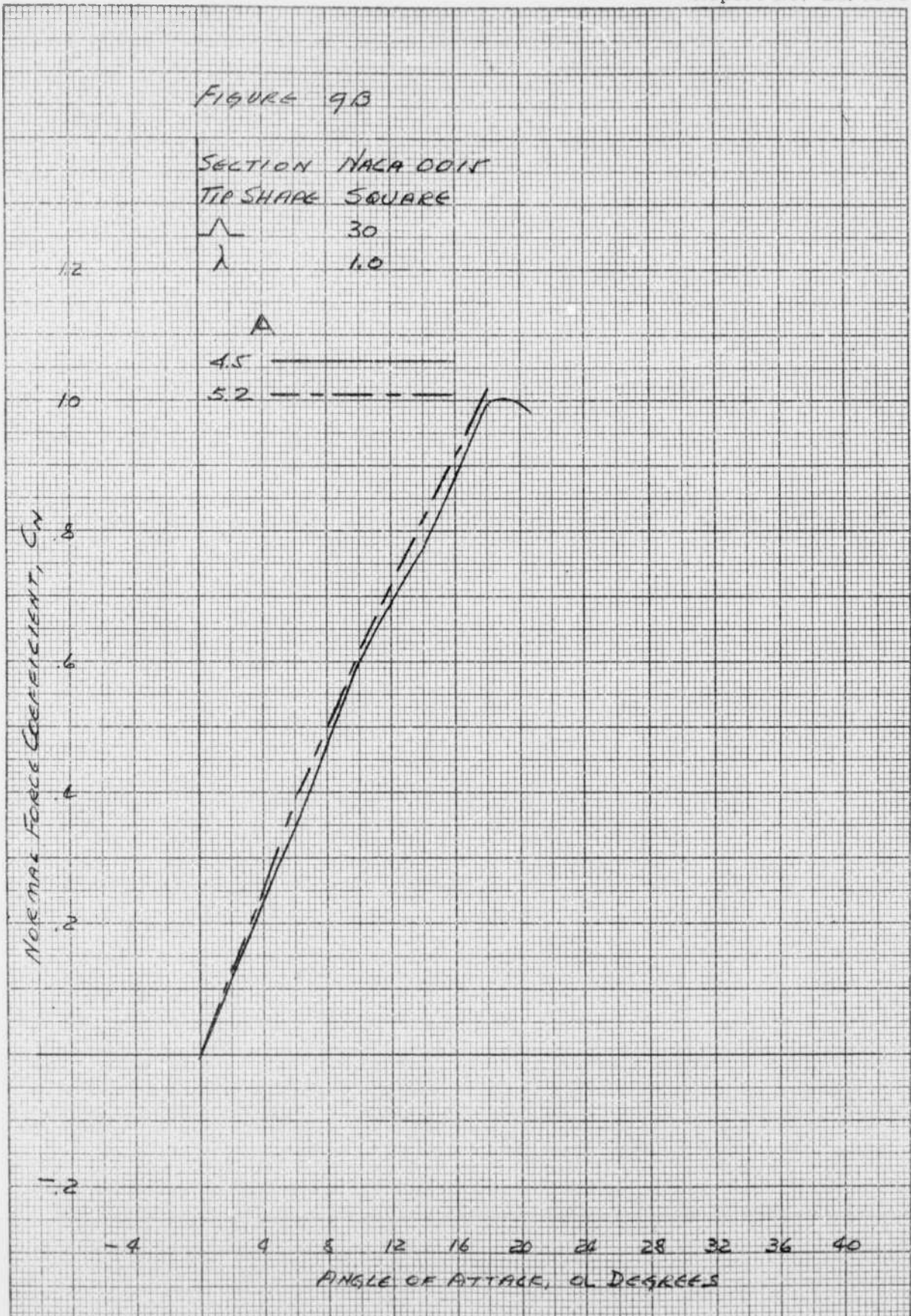


FIGURE 9C

SECTION NACA 0012

TIP SHAPE SQUARE

Λ 30°

λ 1.0

A

4.5 —————

5.2 - - - - -

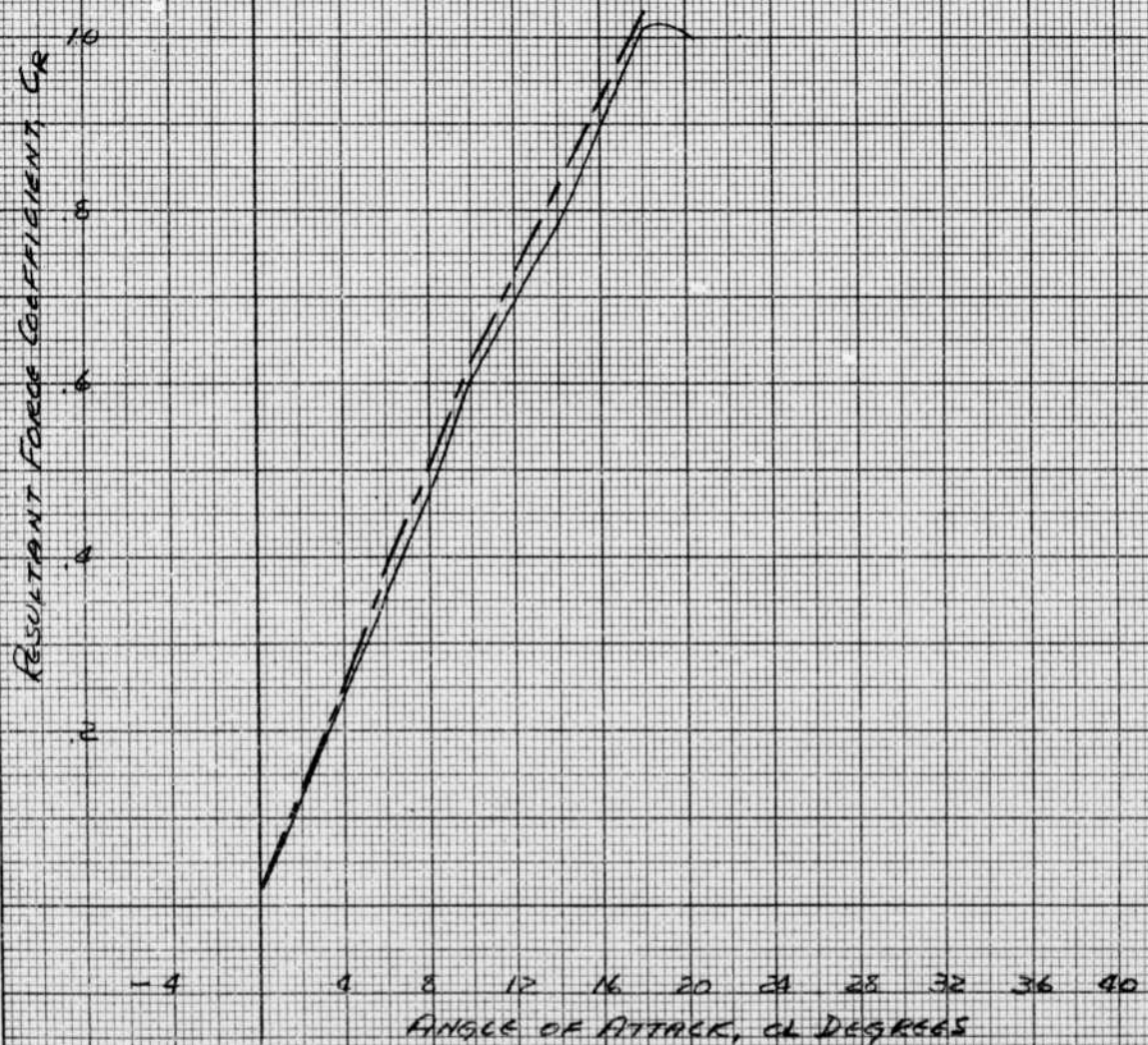


Figure 9D

SECTION NACA 0011
TIP SHAPE SQUARE
 Λ 30°
 λ 1.0

A
4.5 —————
5.2 - - - - -

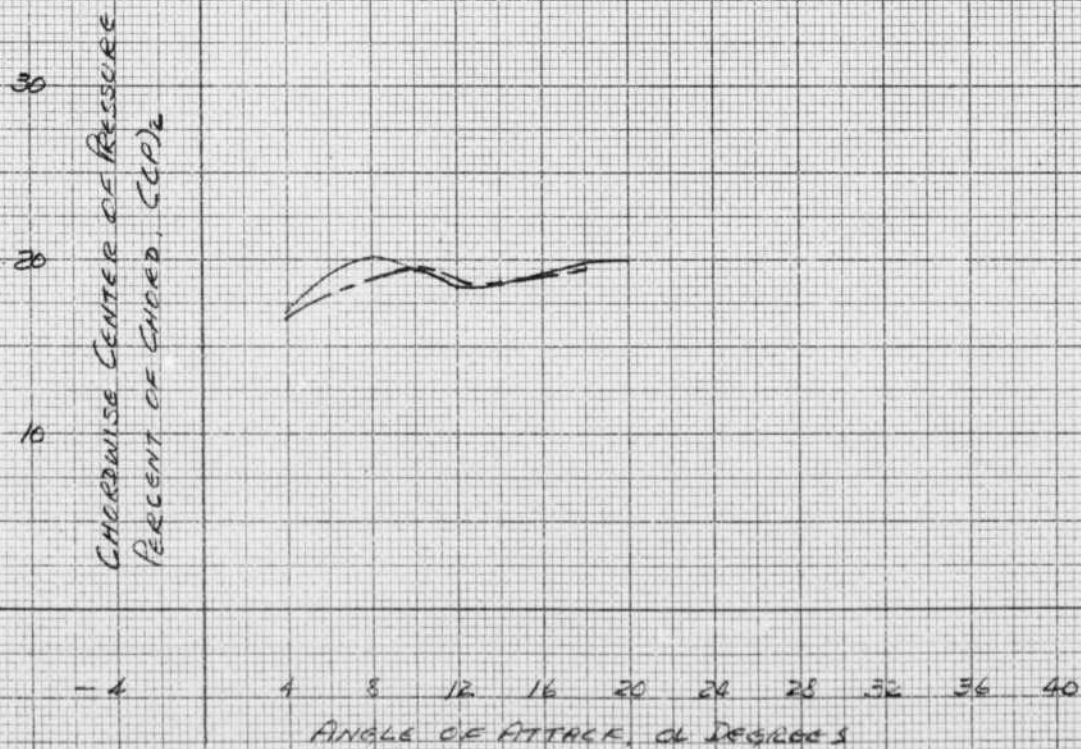


FIGURE 10

SECTION NACA CC15
TIP SHAPE SQUARE

Λ 60
 λ 10

A

1.5 —————
3.0 - - - - -

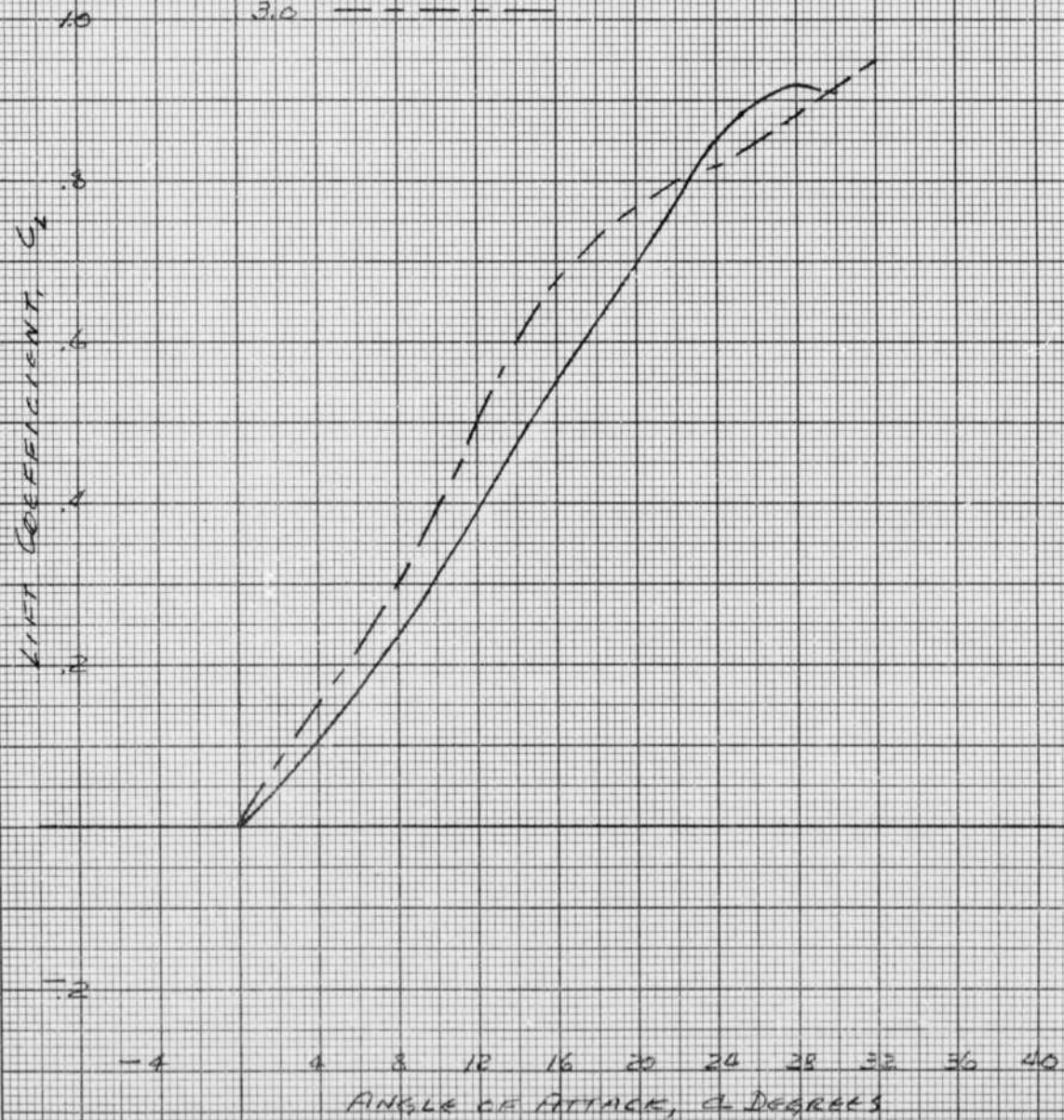


FIGURE 16A

SECTION NACA 0015
TIP SHAPE SQUARE

Λ 60
 λ 10

A
1.5 ———
3.0 - - - - -

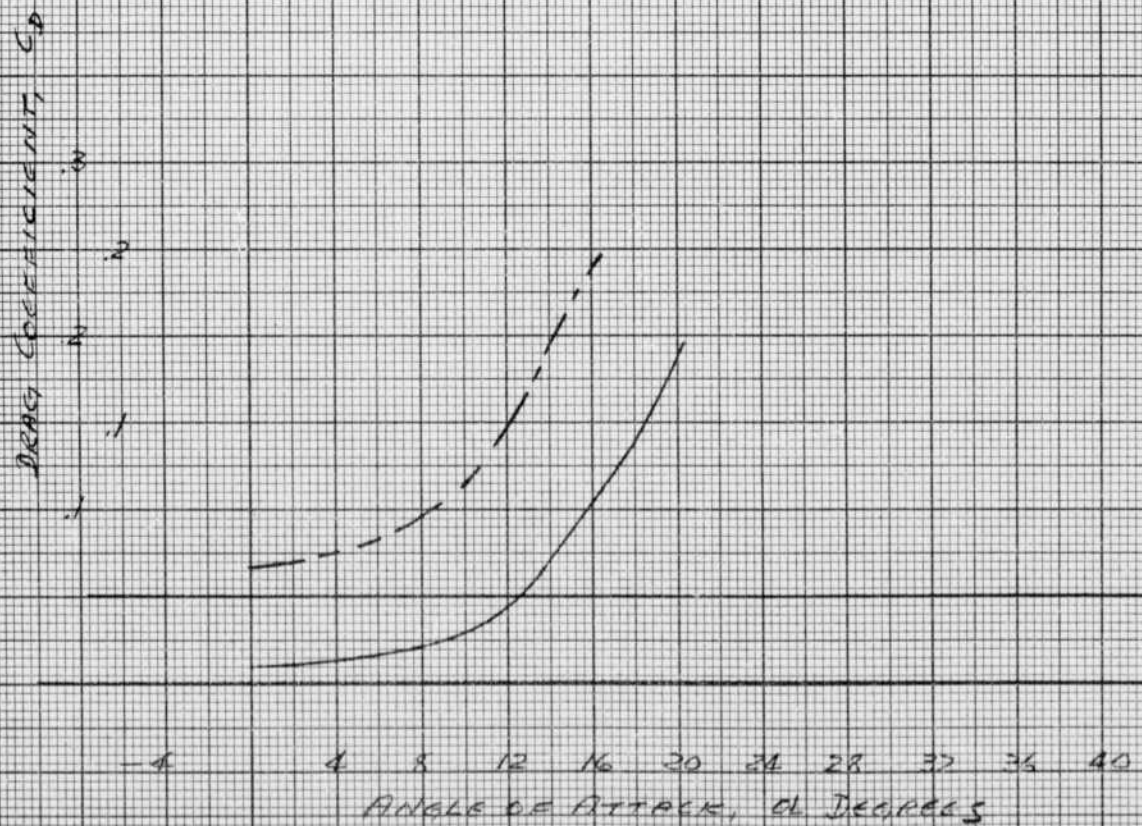


FIGURE 10B

SECTION NACA 0015
TIP SHARP SQUARE

Λ 60
 λ 1.0

A

1.5

3.0

10

NORMAL FORCE COEFFICIENT, C_N

8

6

4

2

-2

-4

4

8

12

16

20

24

28

32

36

40

ANGLE OF ATTACK, α DEGREES

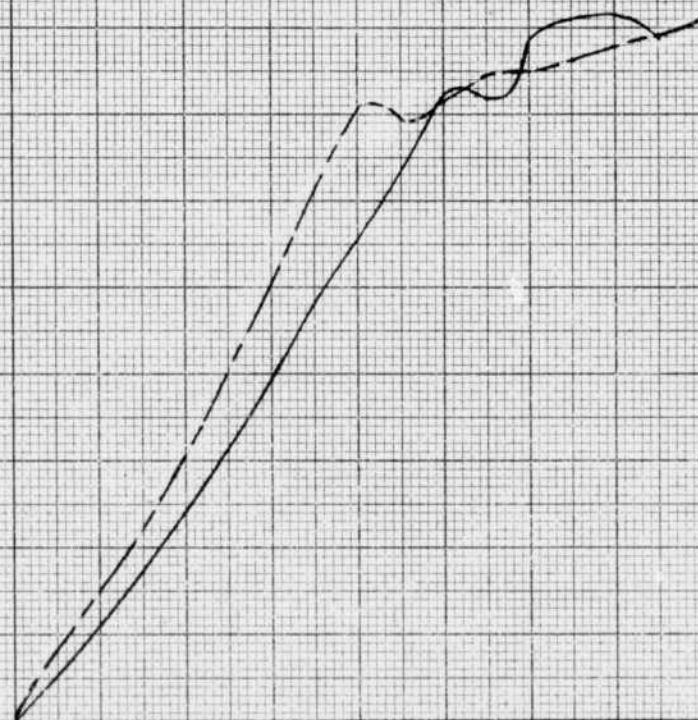


FIGURE 10C

SECTION NACA 0015

TIP SHAPE SQUARE

 Λ 60 λ 1.0

A

1.5

3.0

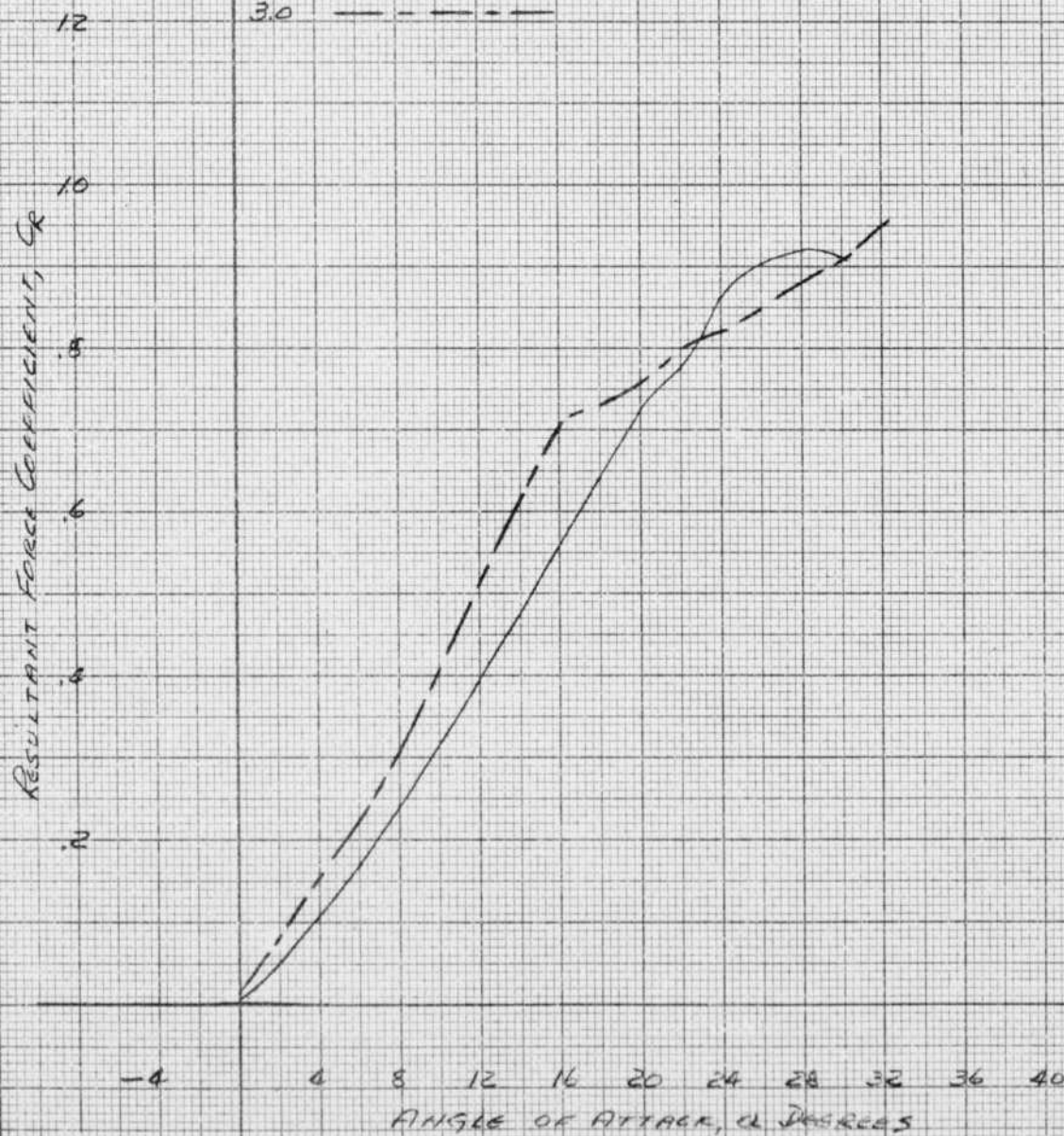


FIGURE 10D

SECTION NACA 0015
TIP SHAPE SQUARE

△

A

15 —————
3.0 - - - - -

CHORDWISE CENTER OF PRESSURE
PERCENT OF CHORD, (C_{CP})_x

30

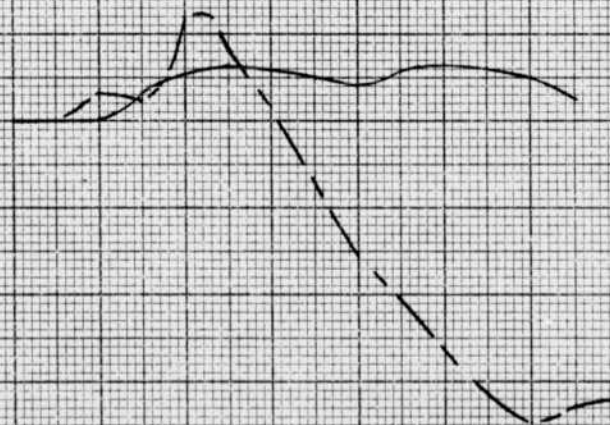
20

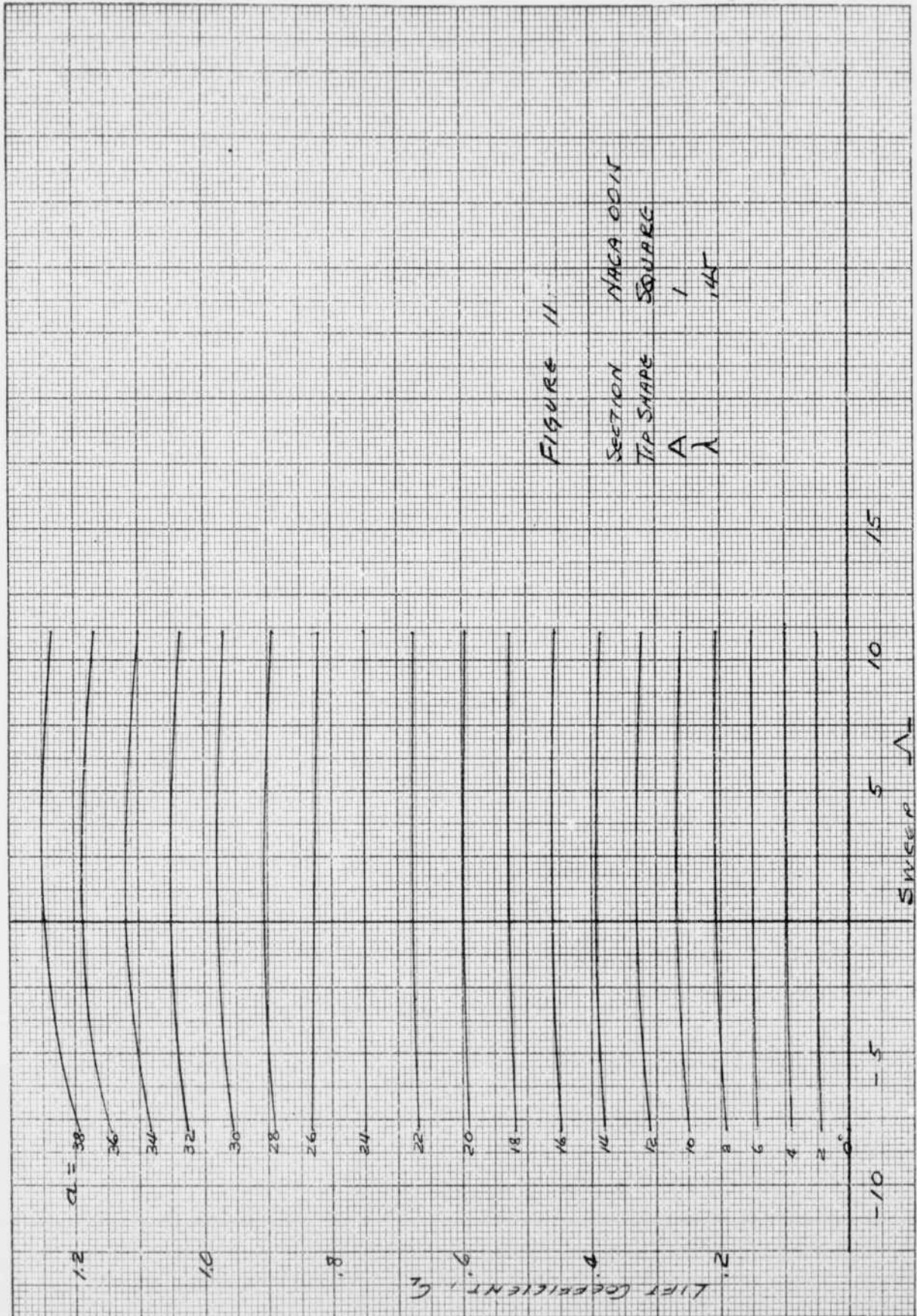
10

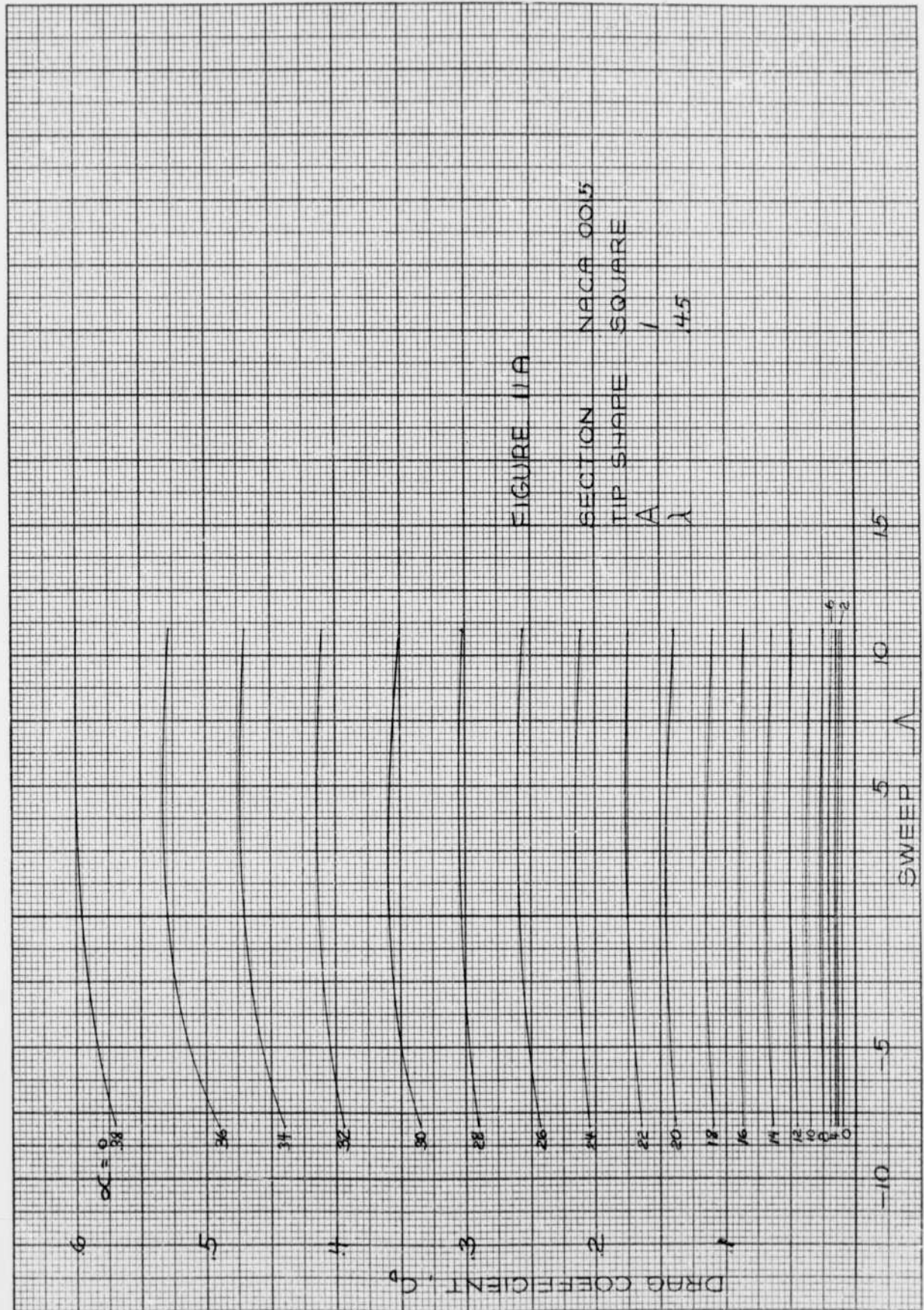
-4

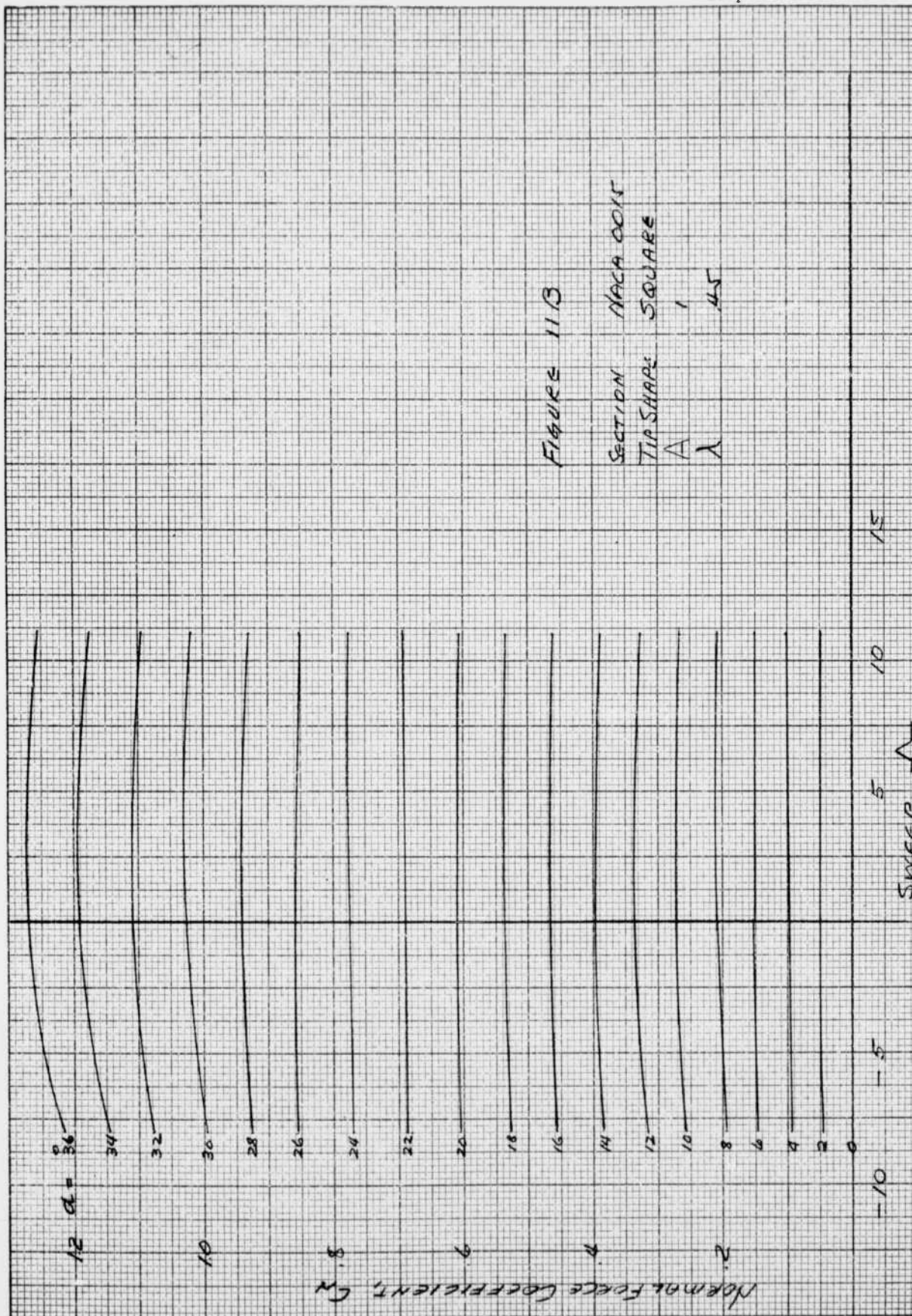
4 8 12 16 20 24 28 32 36 40

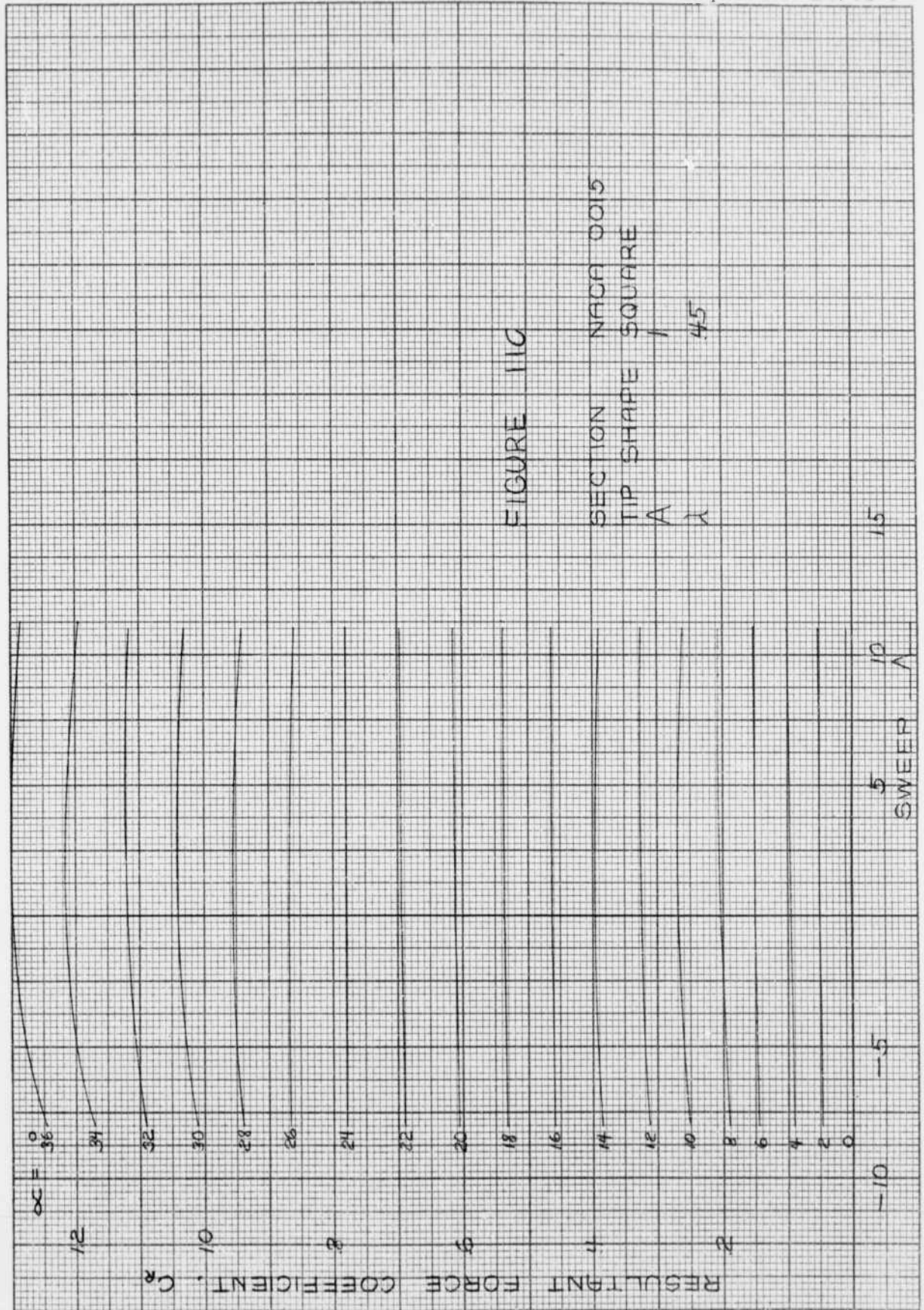
ANGLE OF ATTACK, α , DEGREES

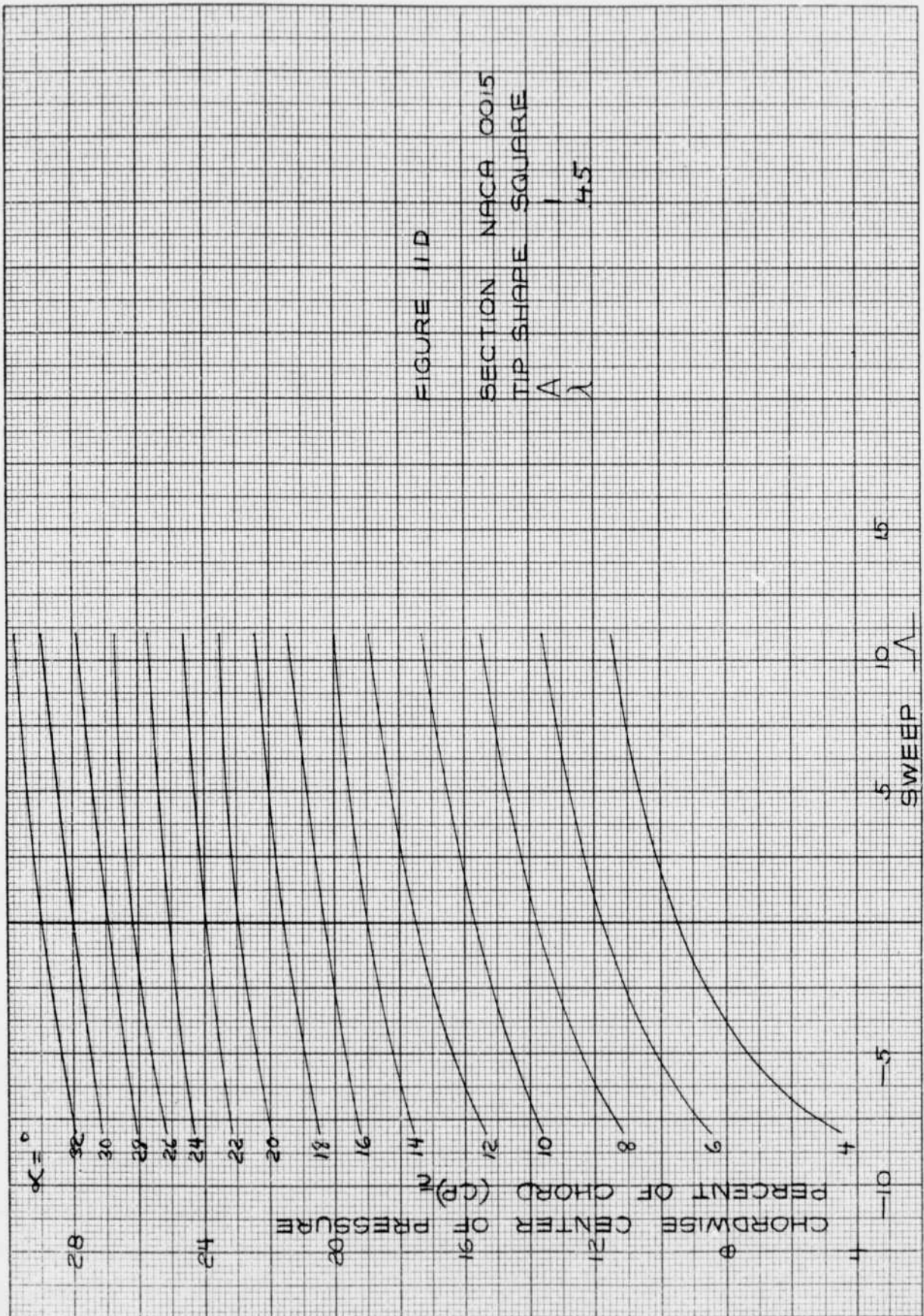


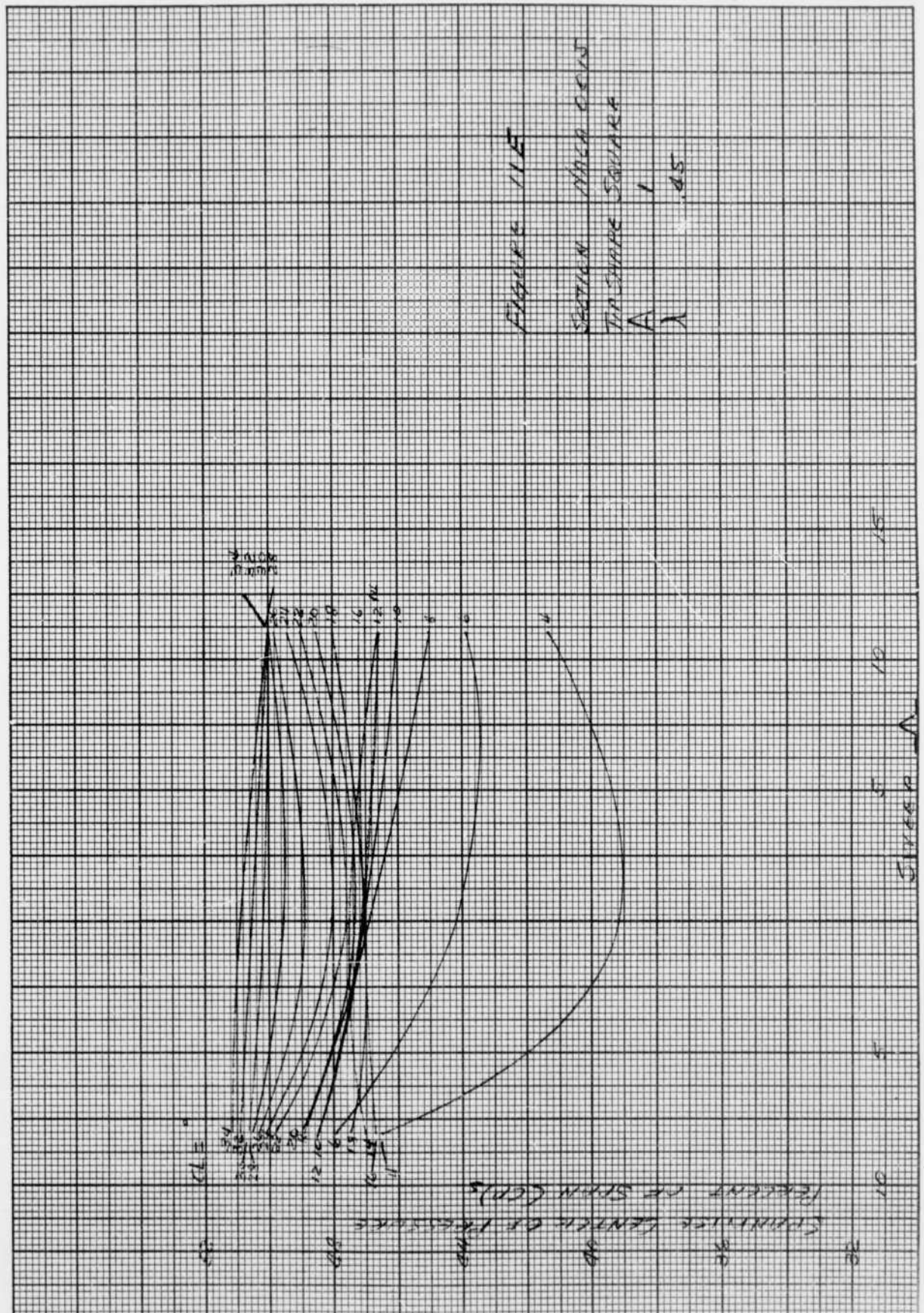


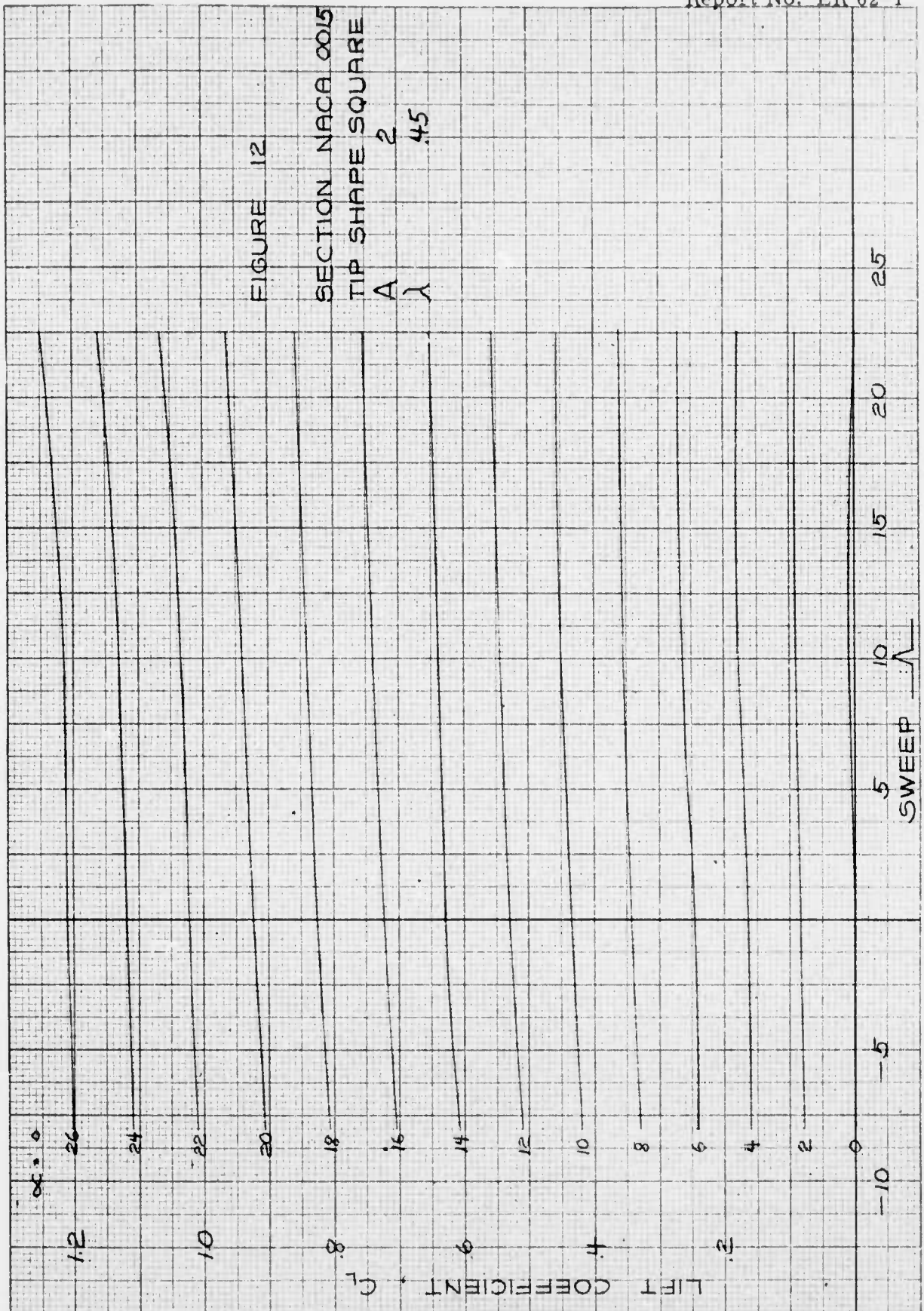


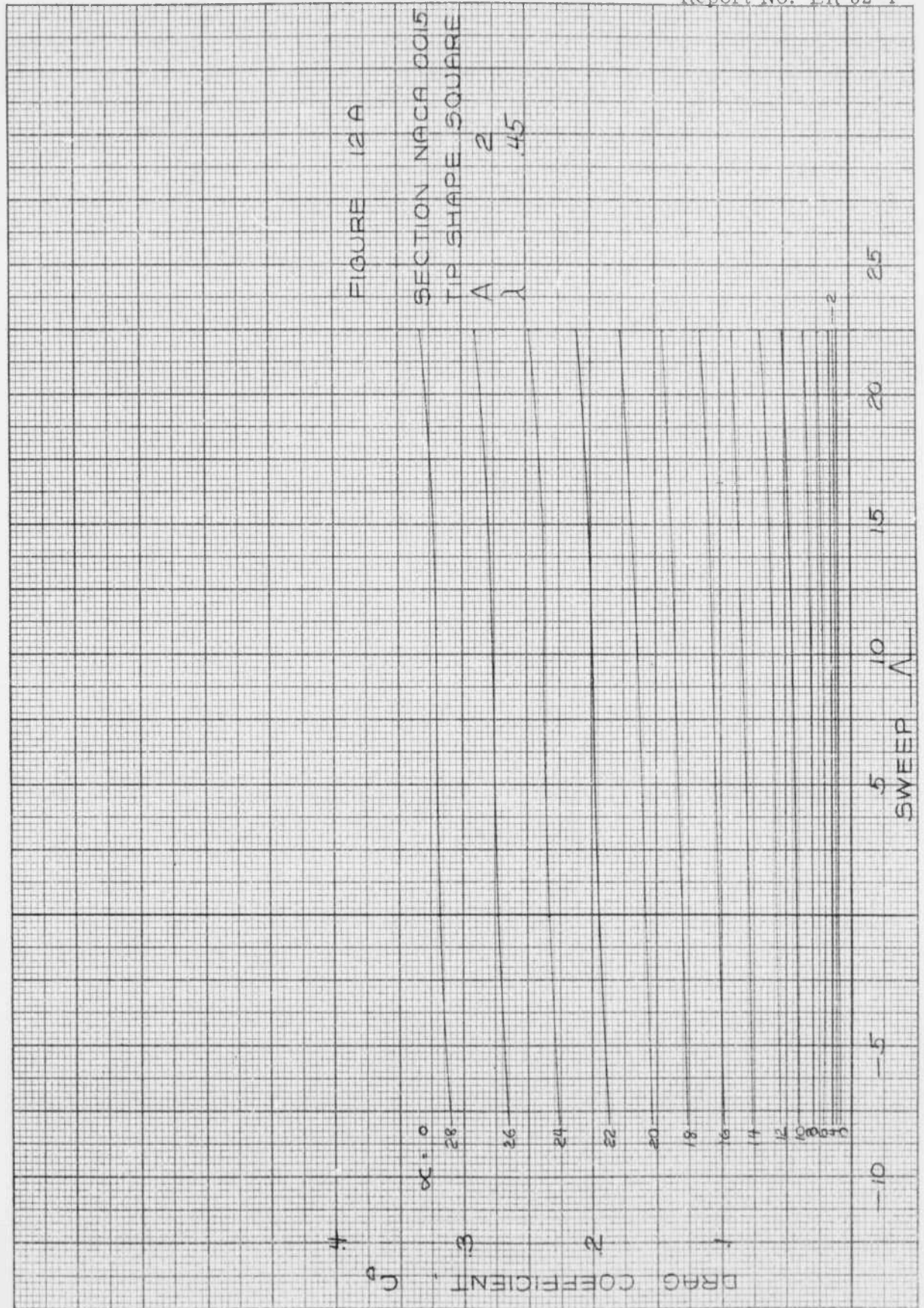


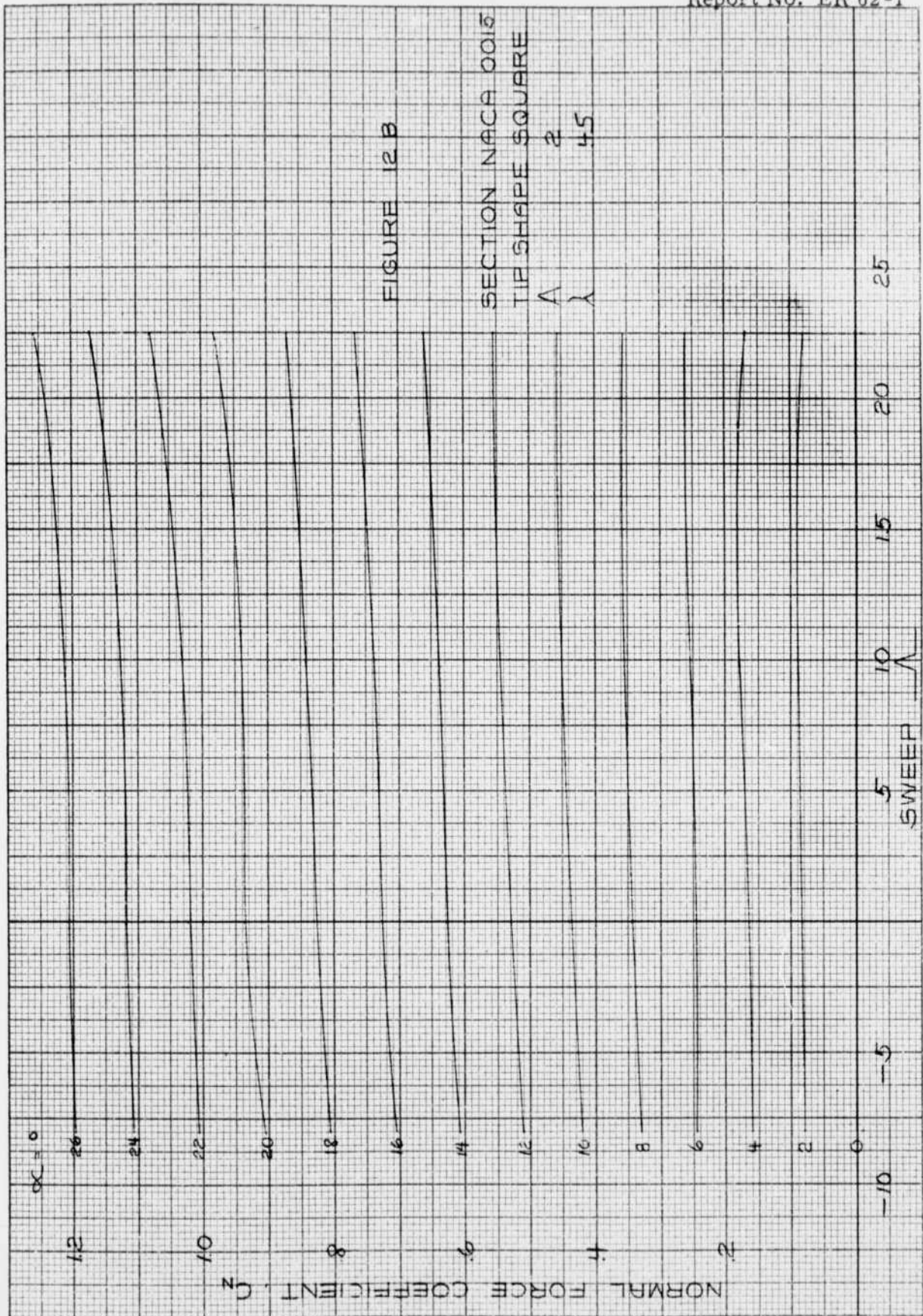


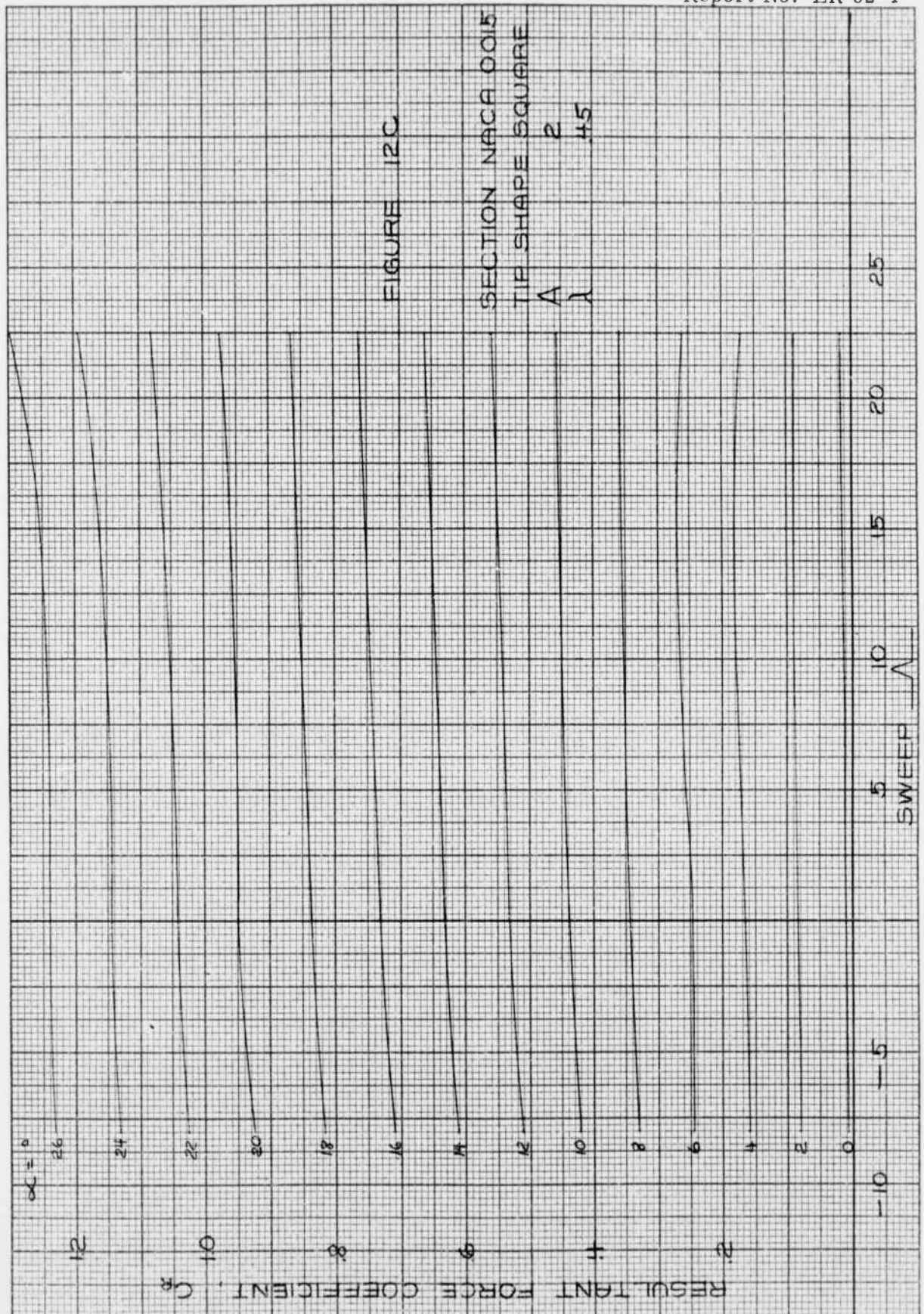


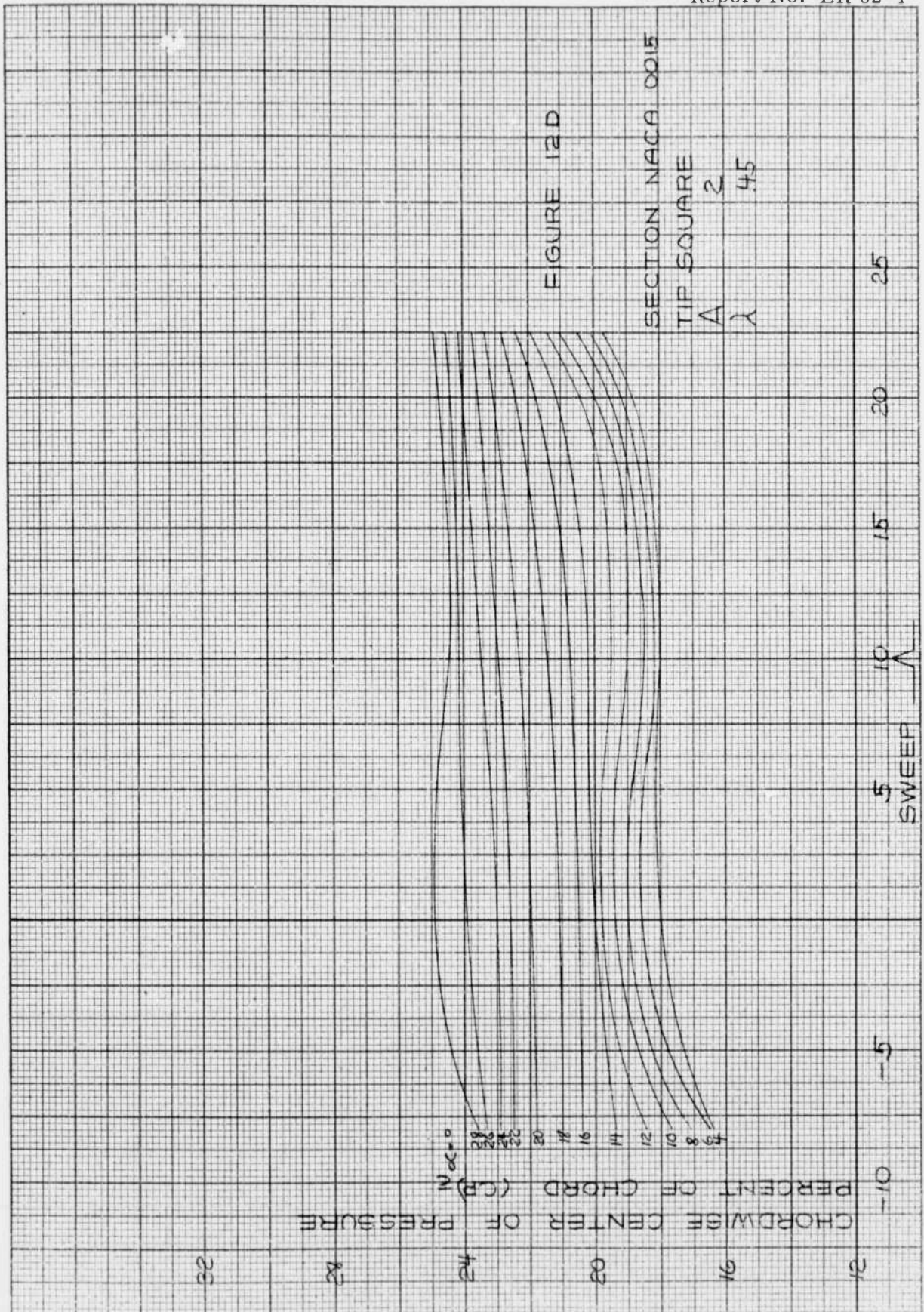


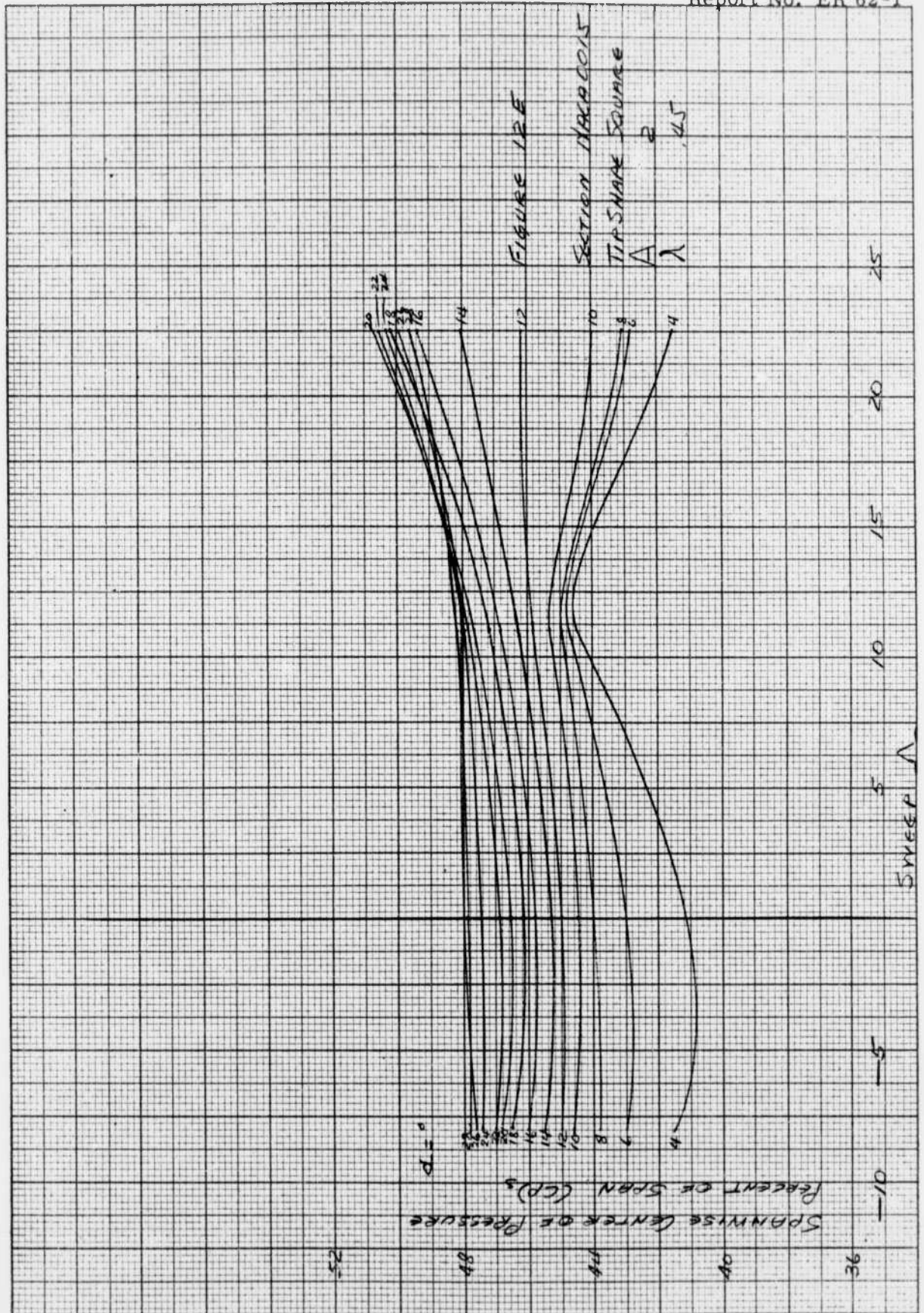


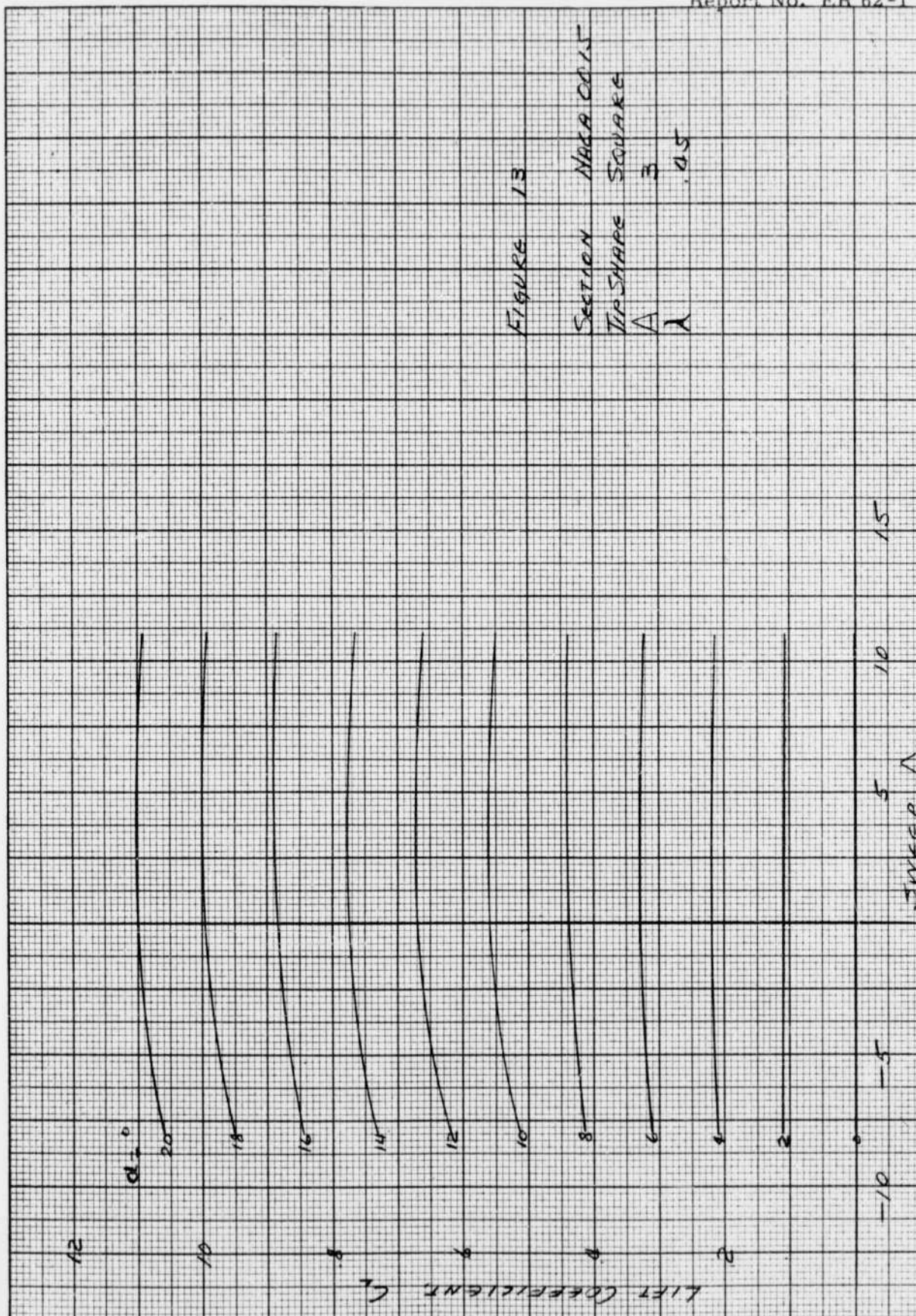


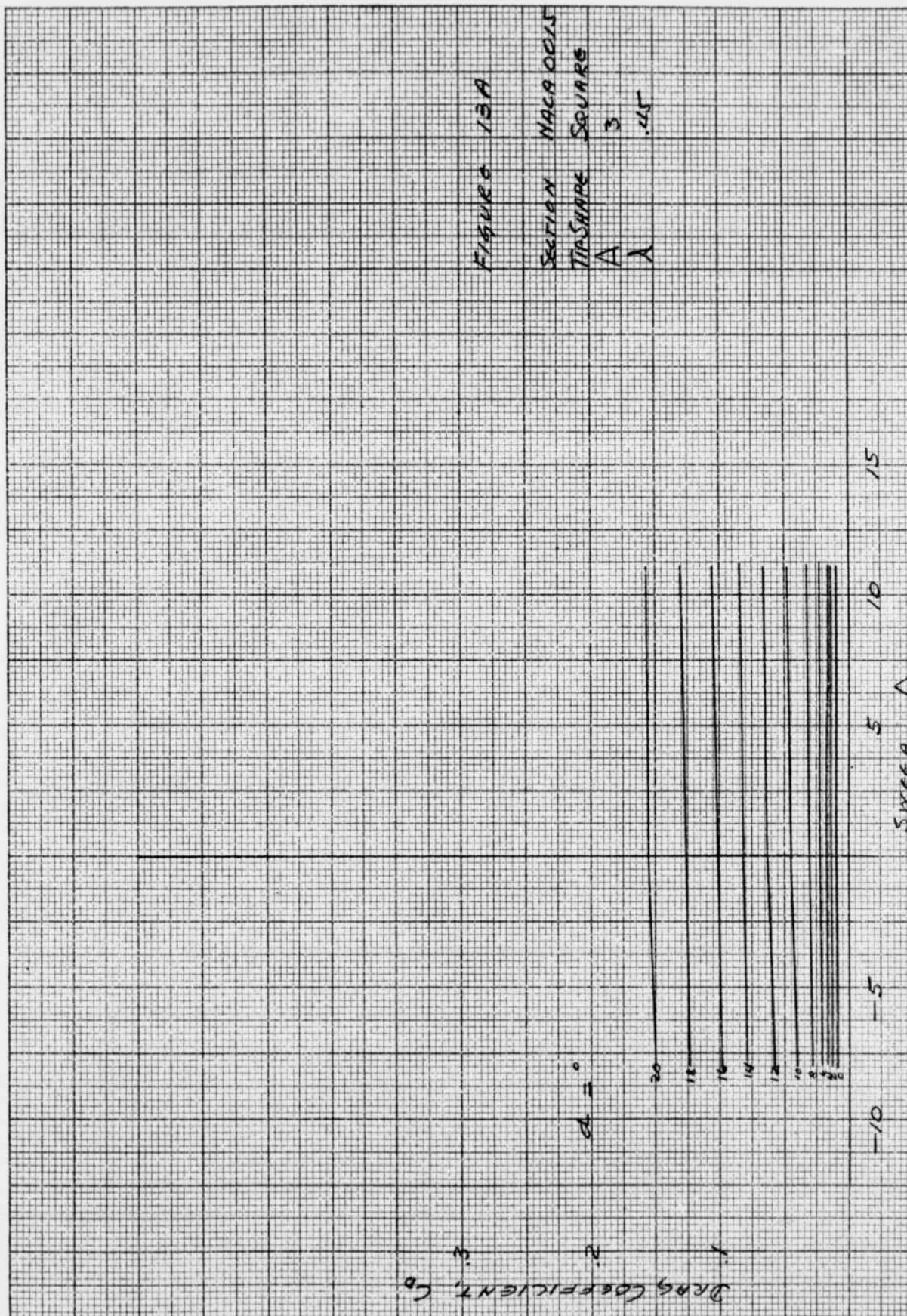


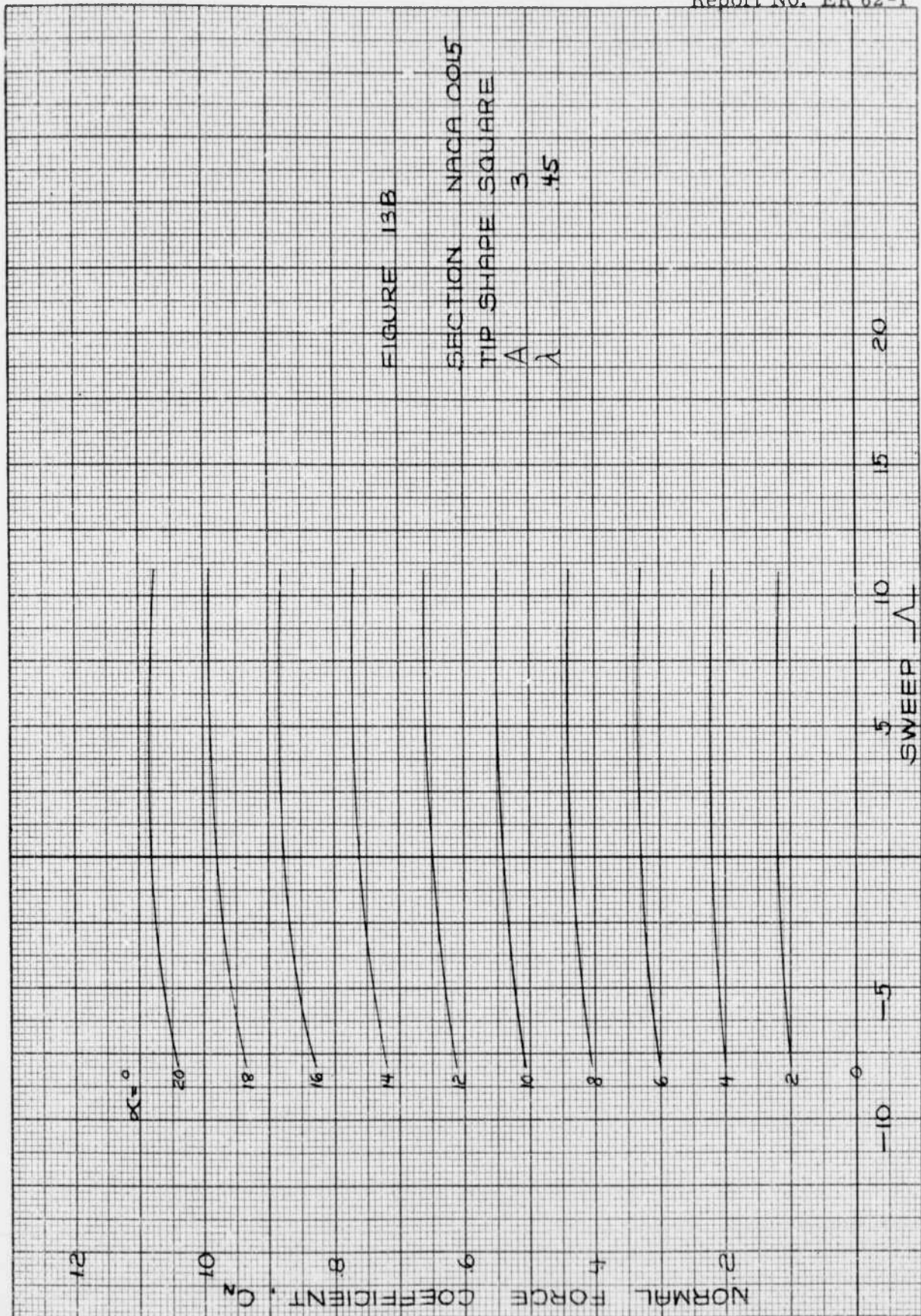


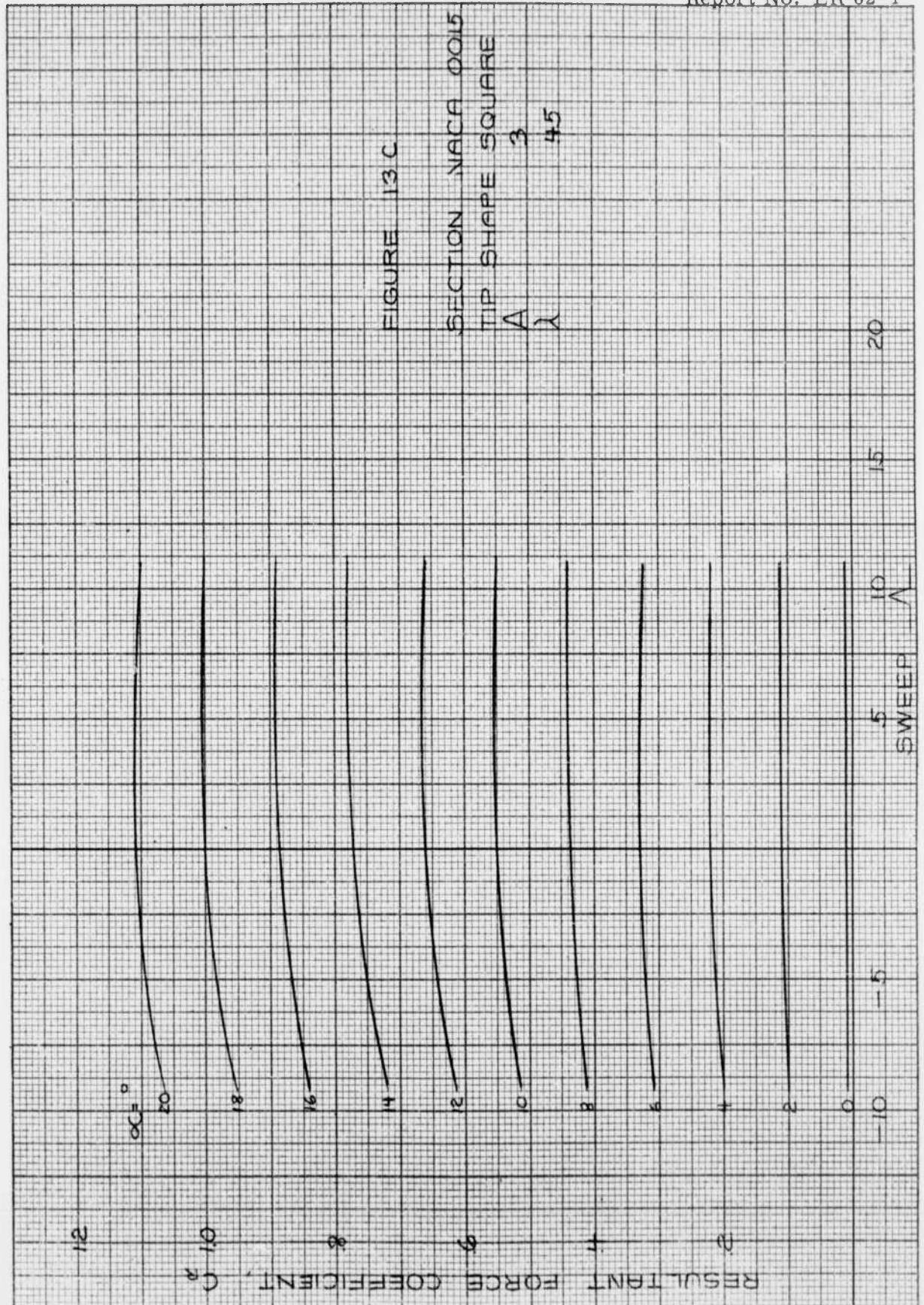


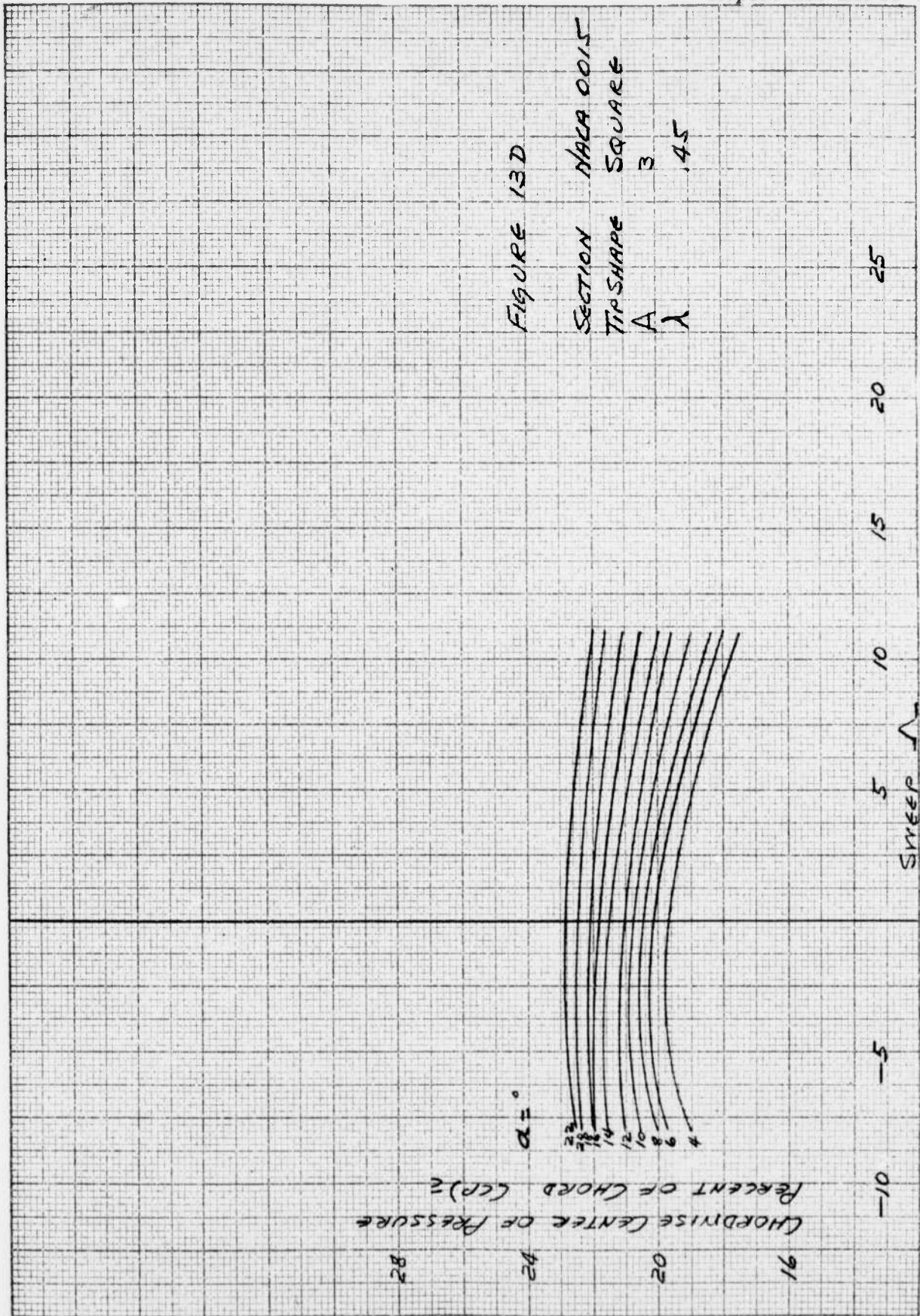












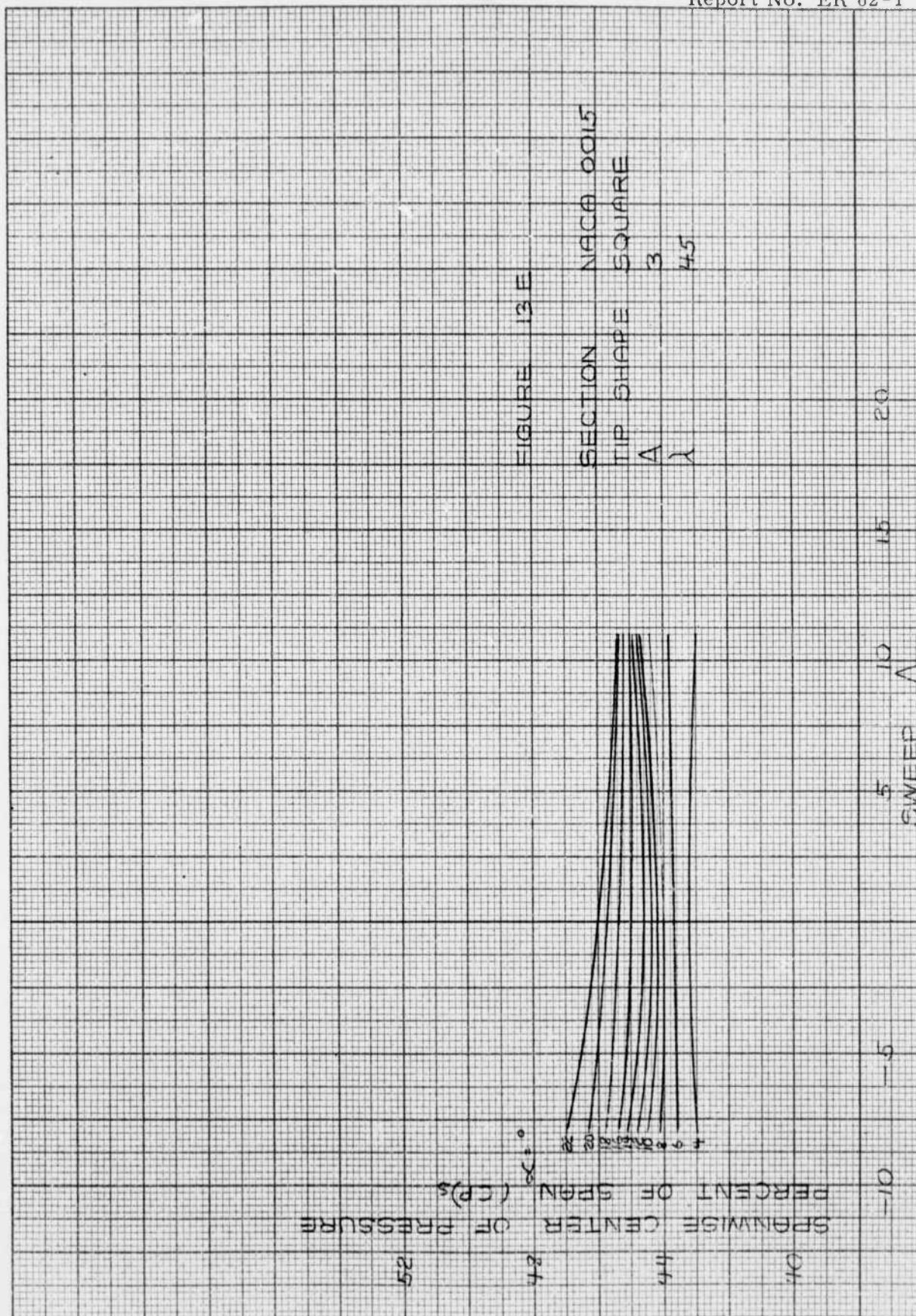
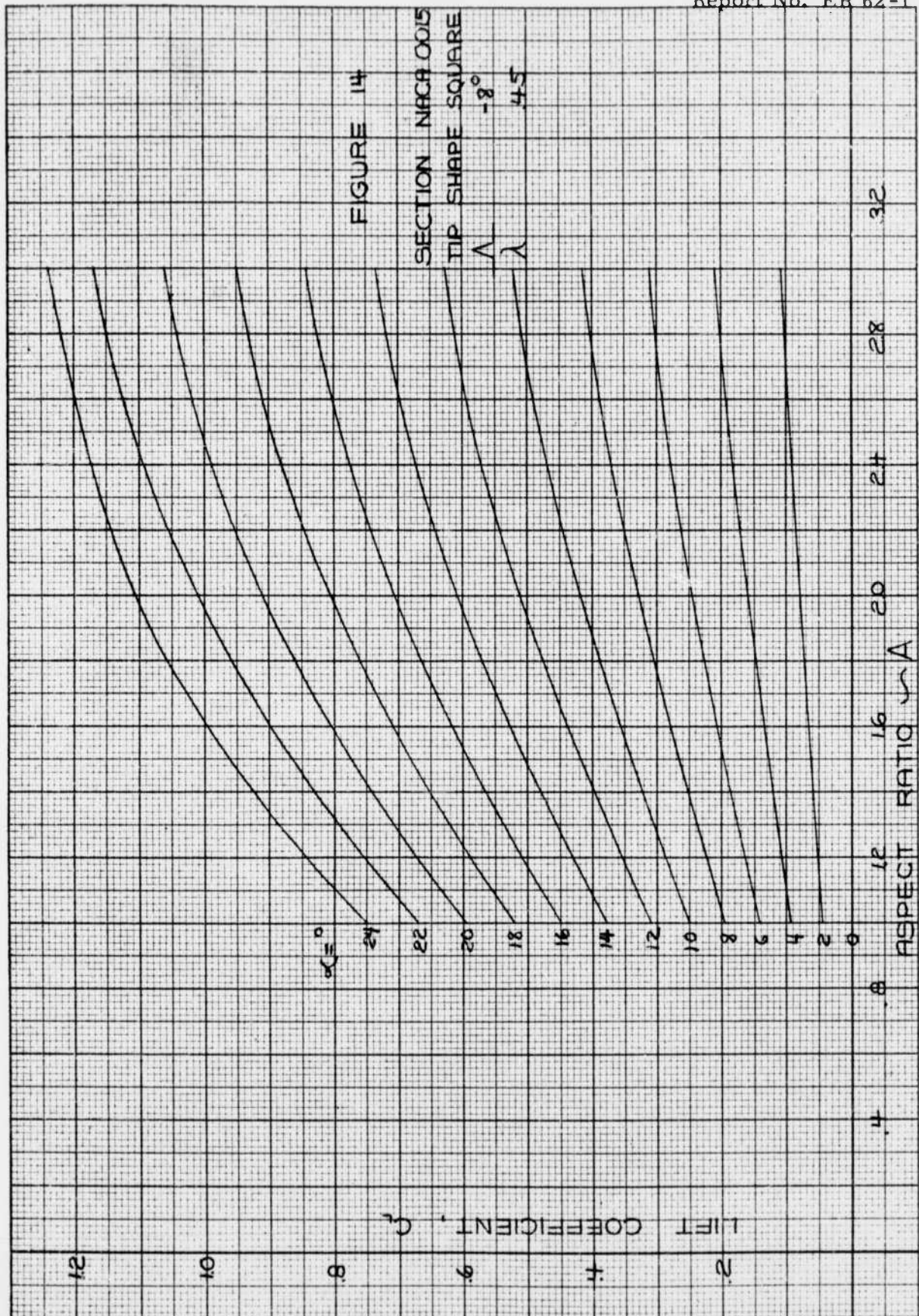
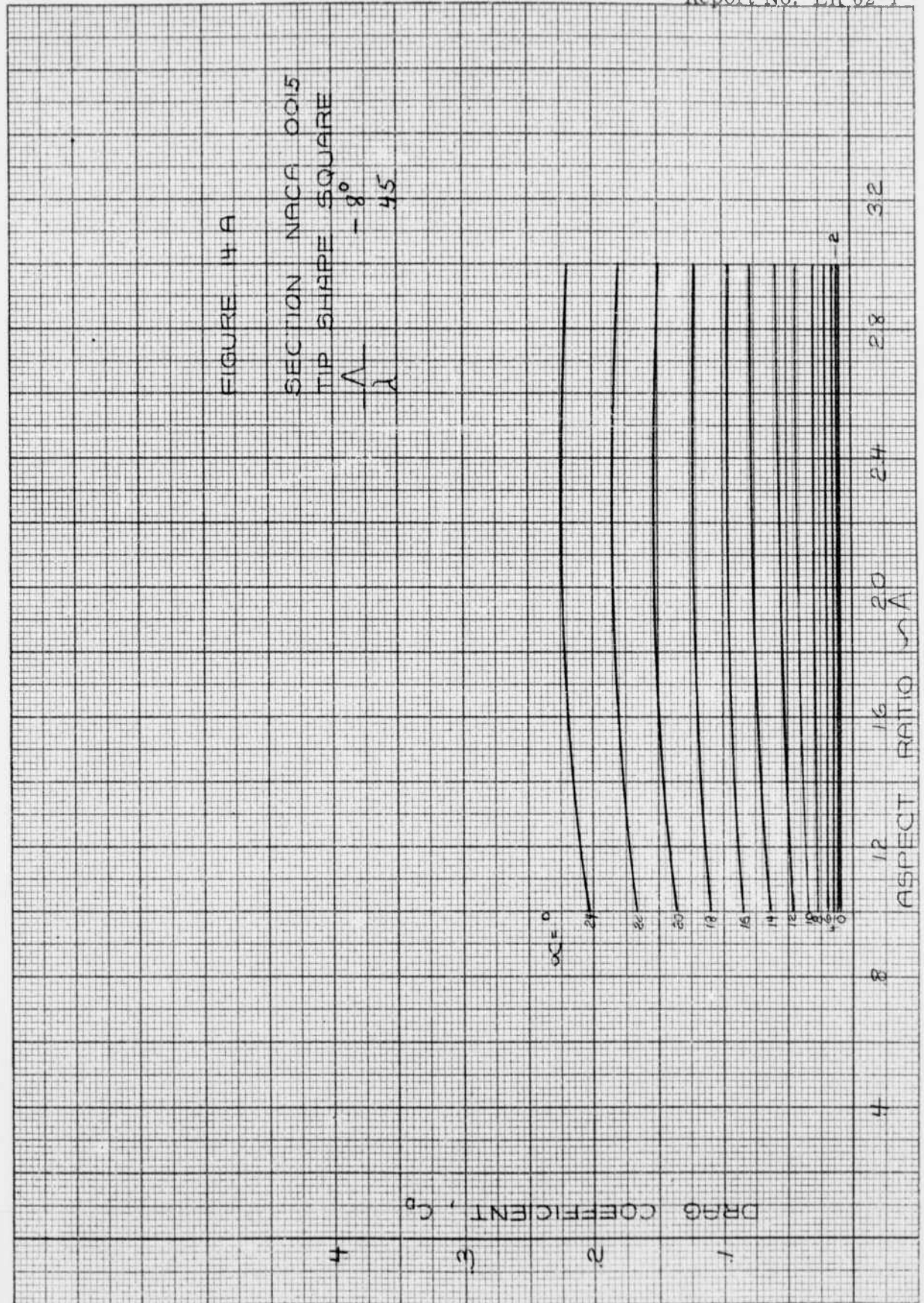
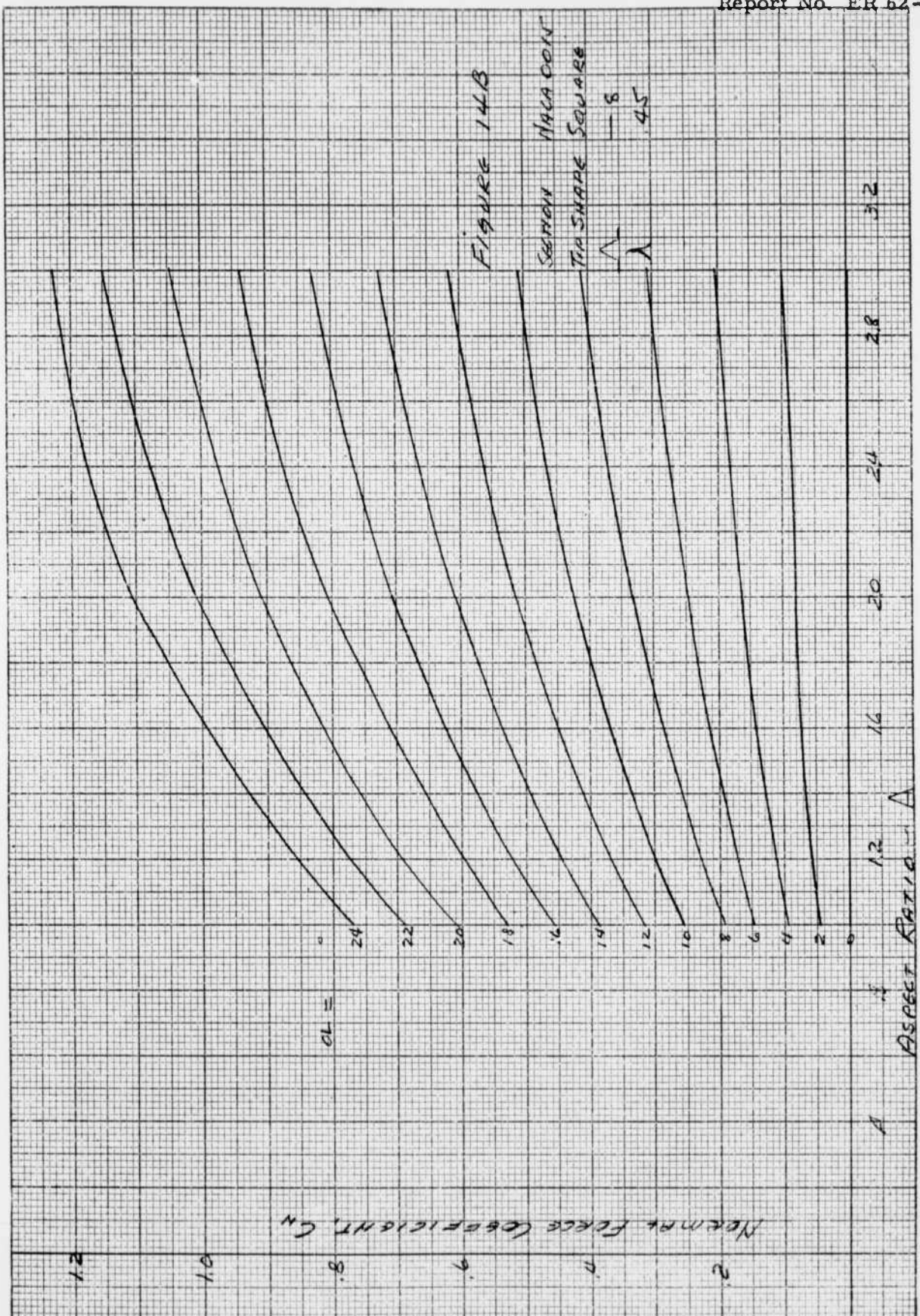
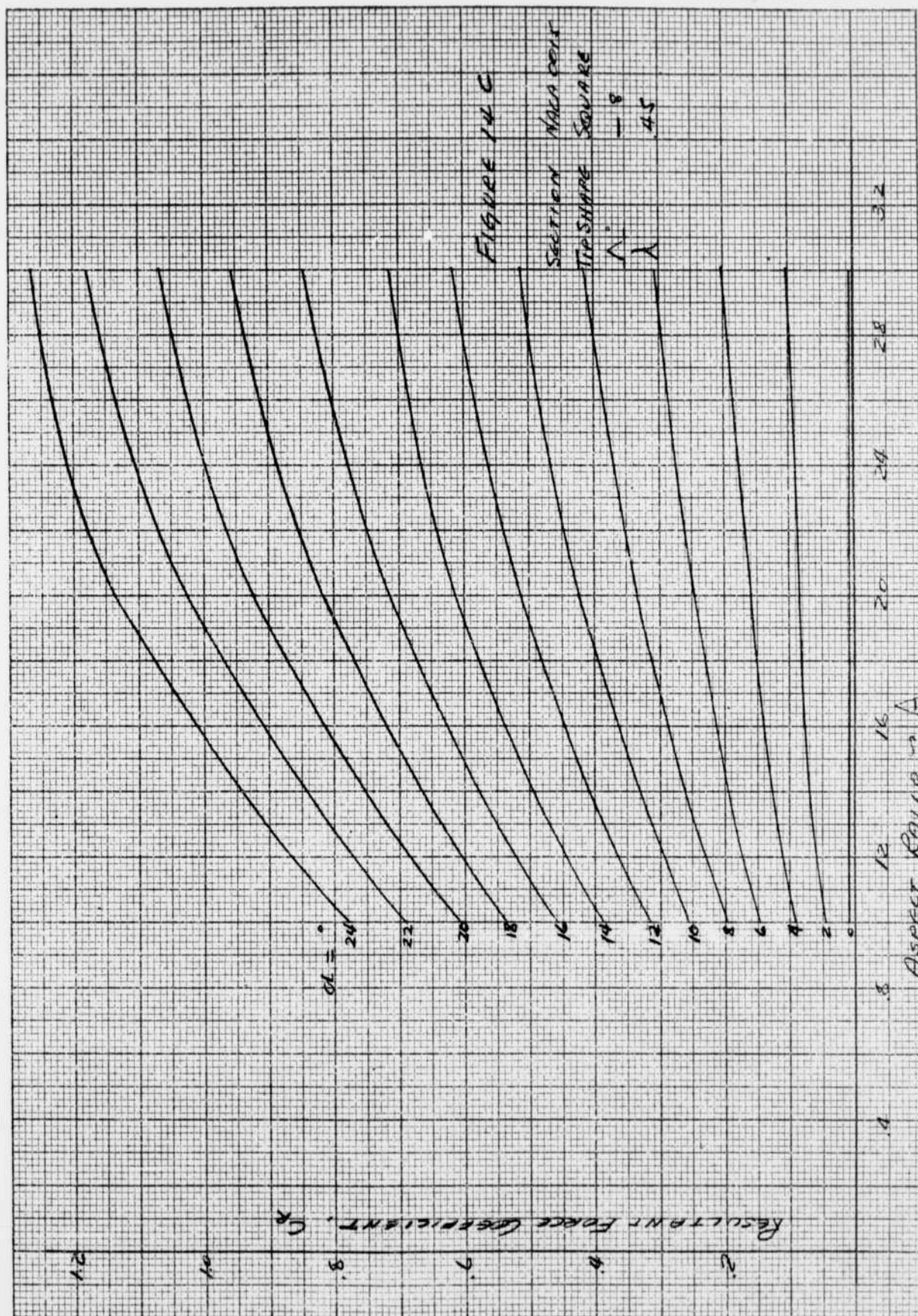


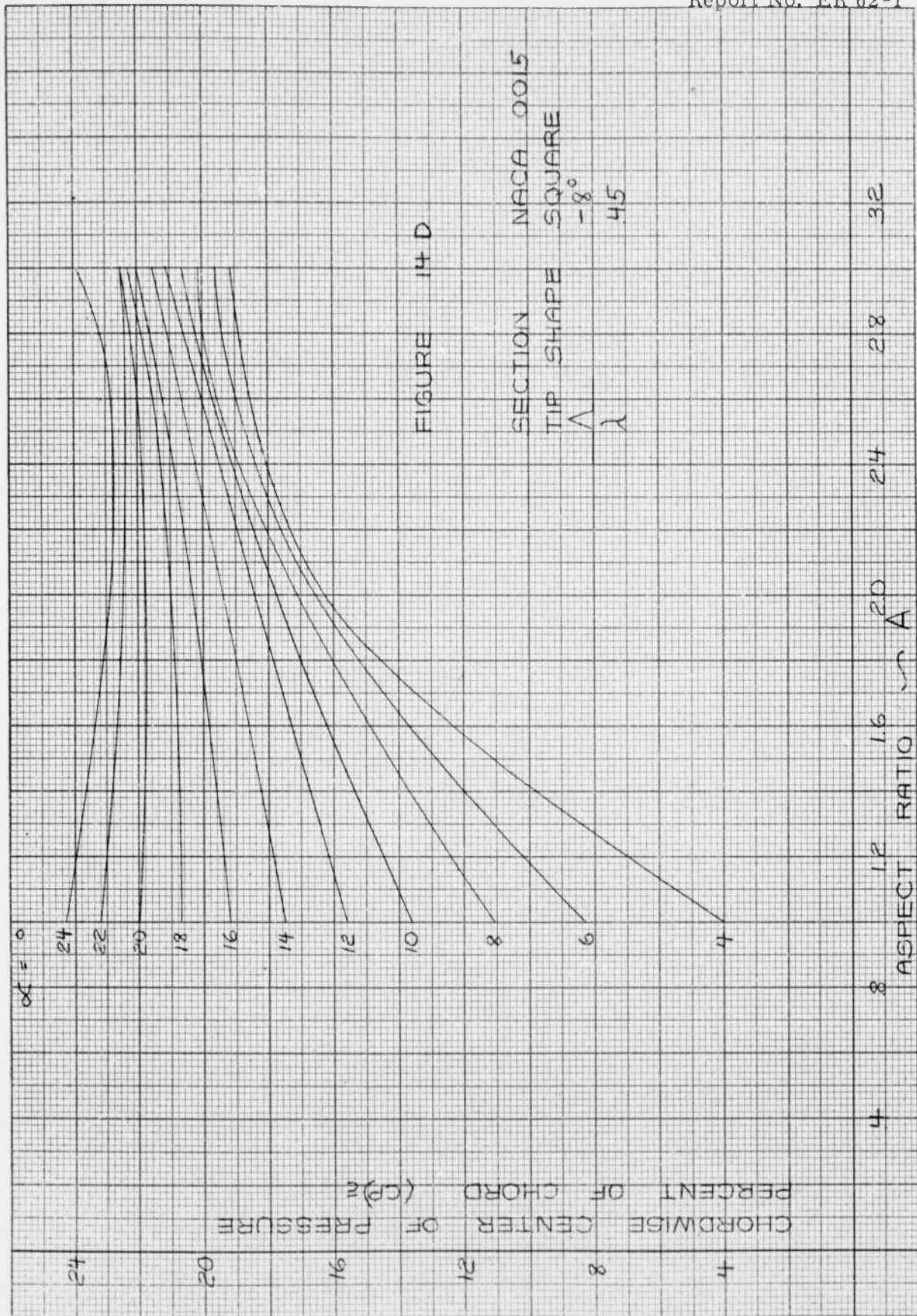
FIGURE 13E
SECTION NACA 0015
TIP SHAPE SQUARE
A 1 3 45

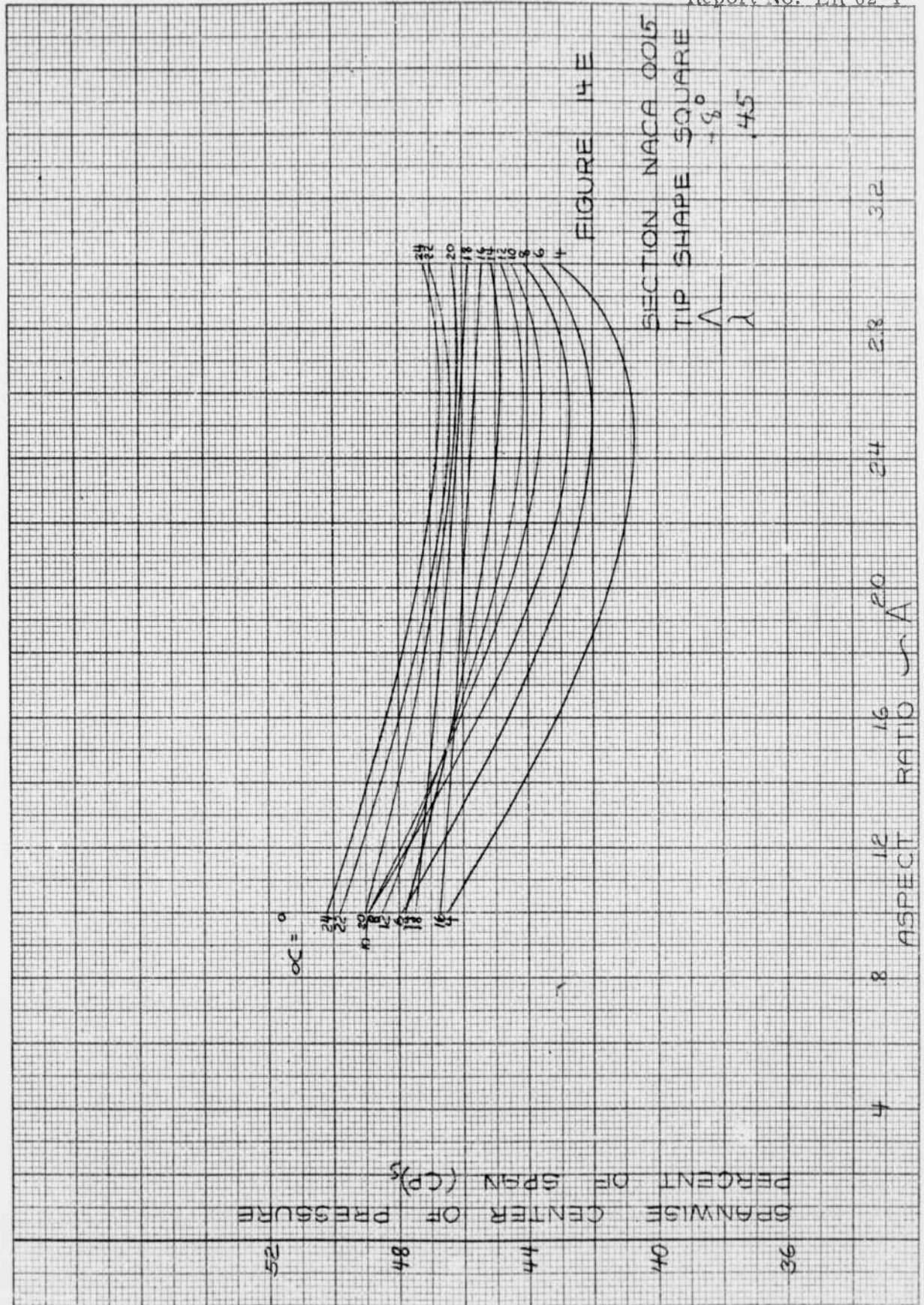


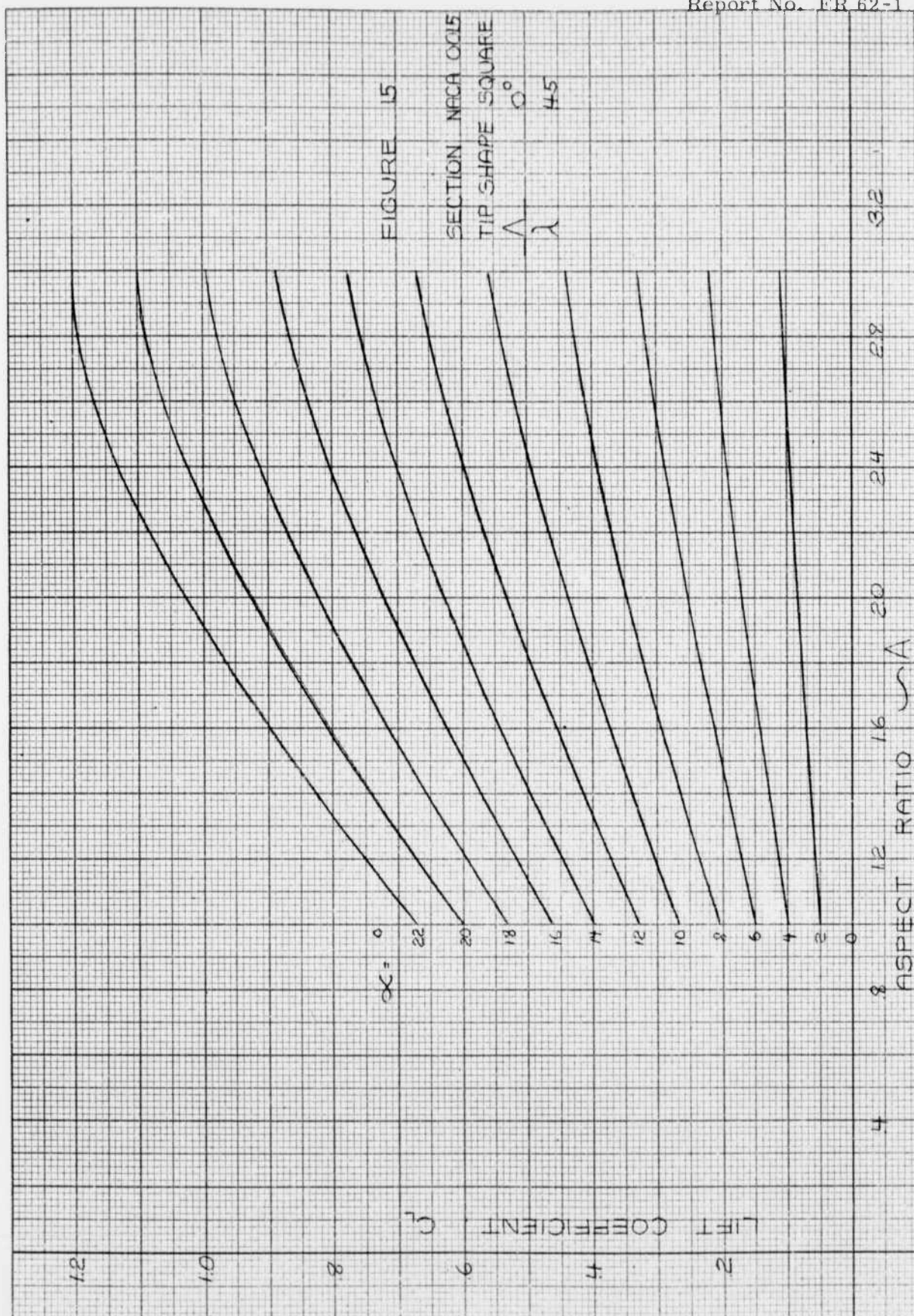


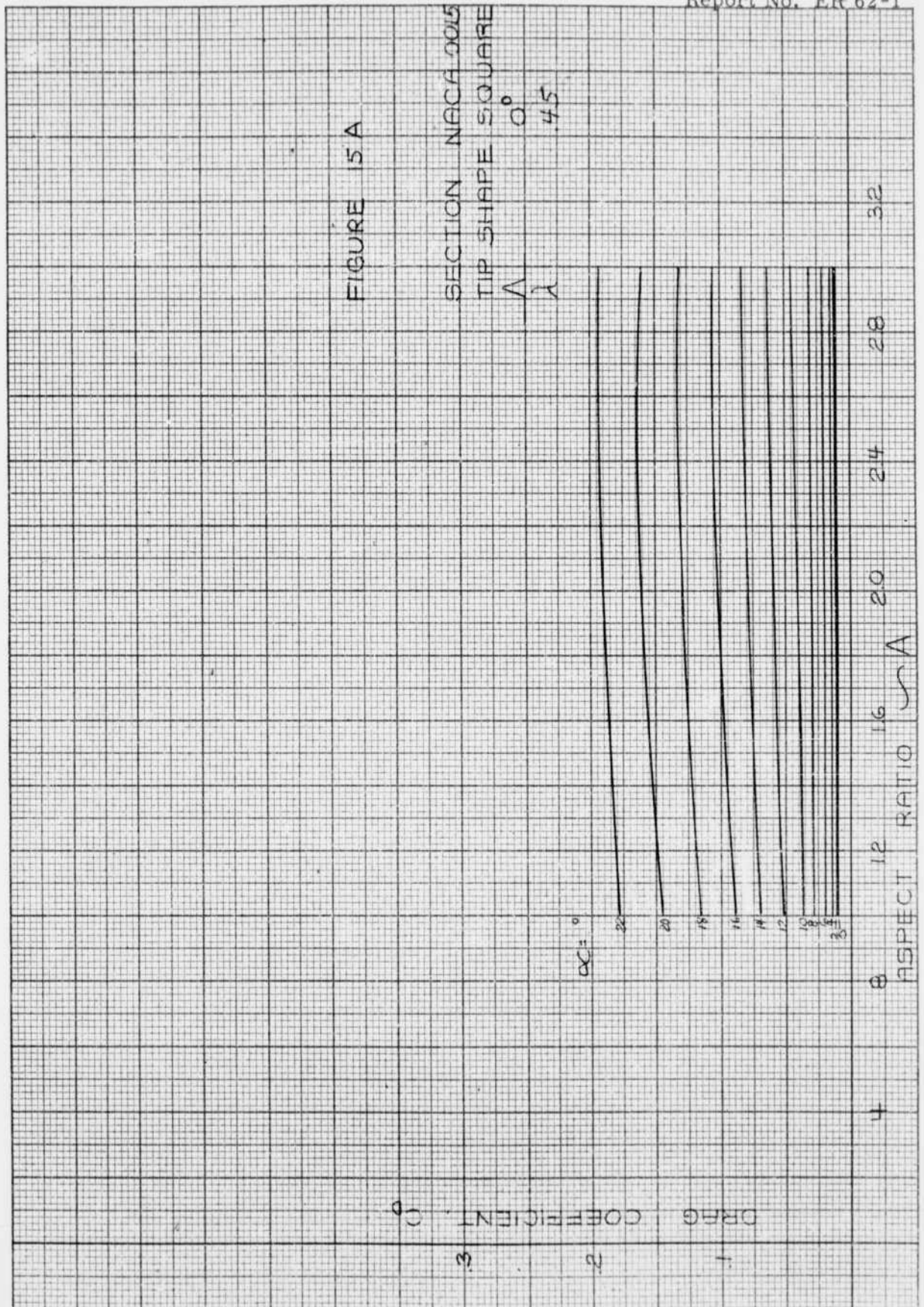


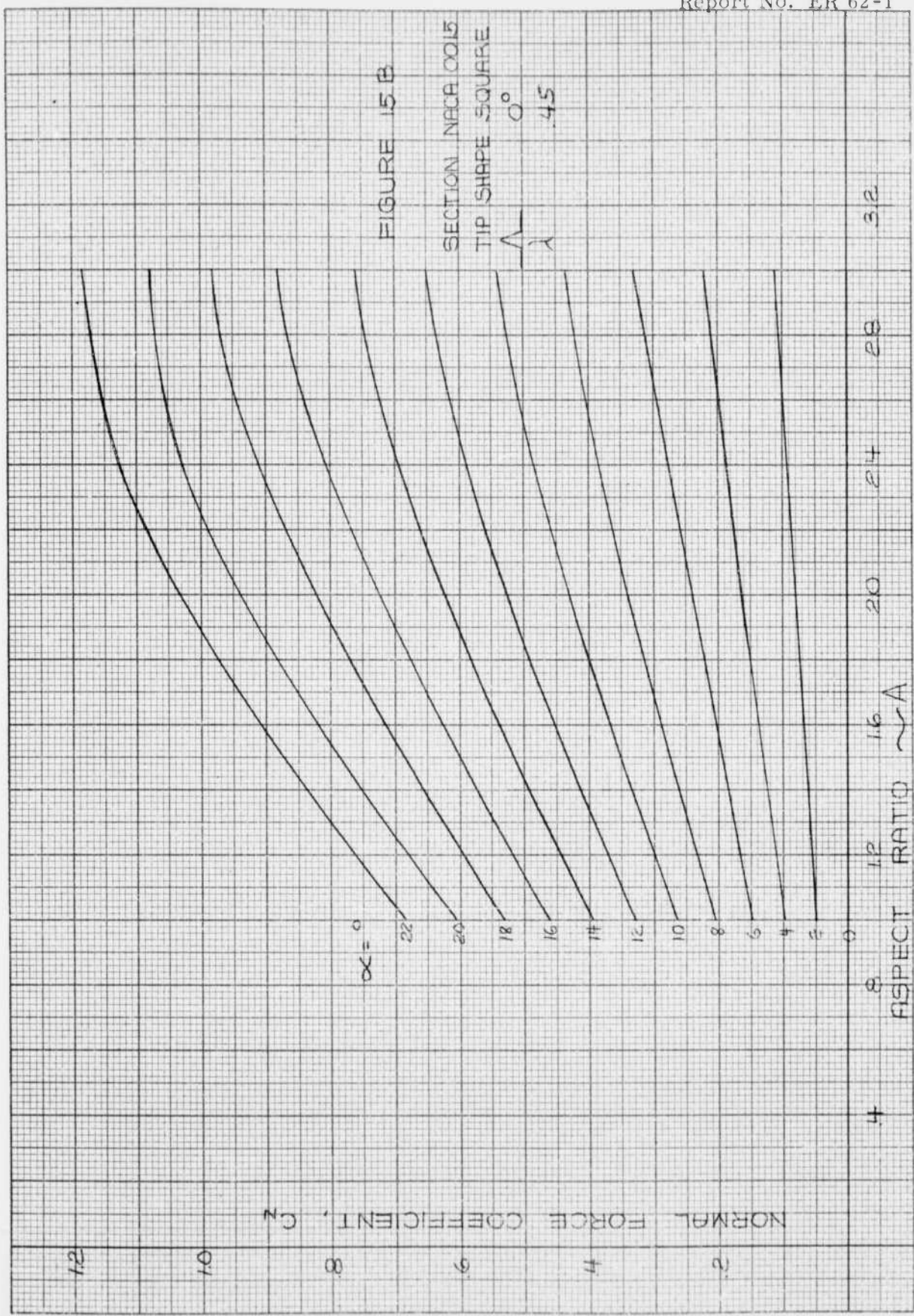


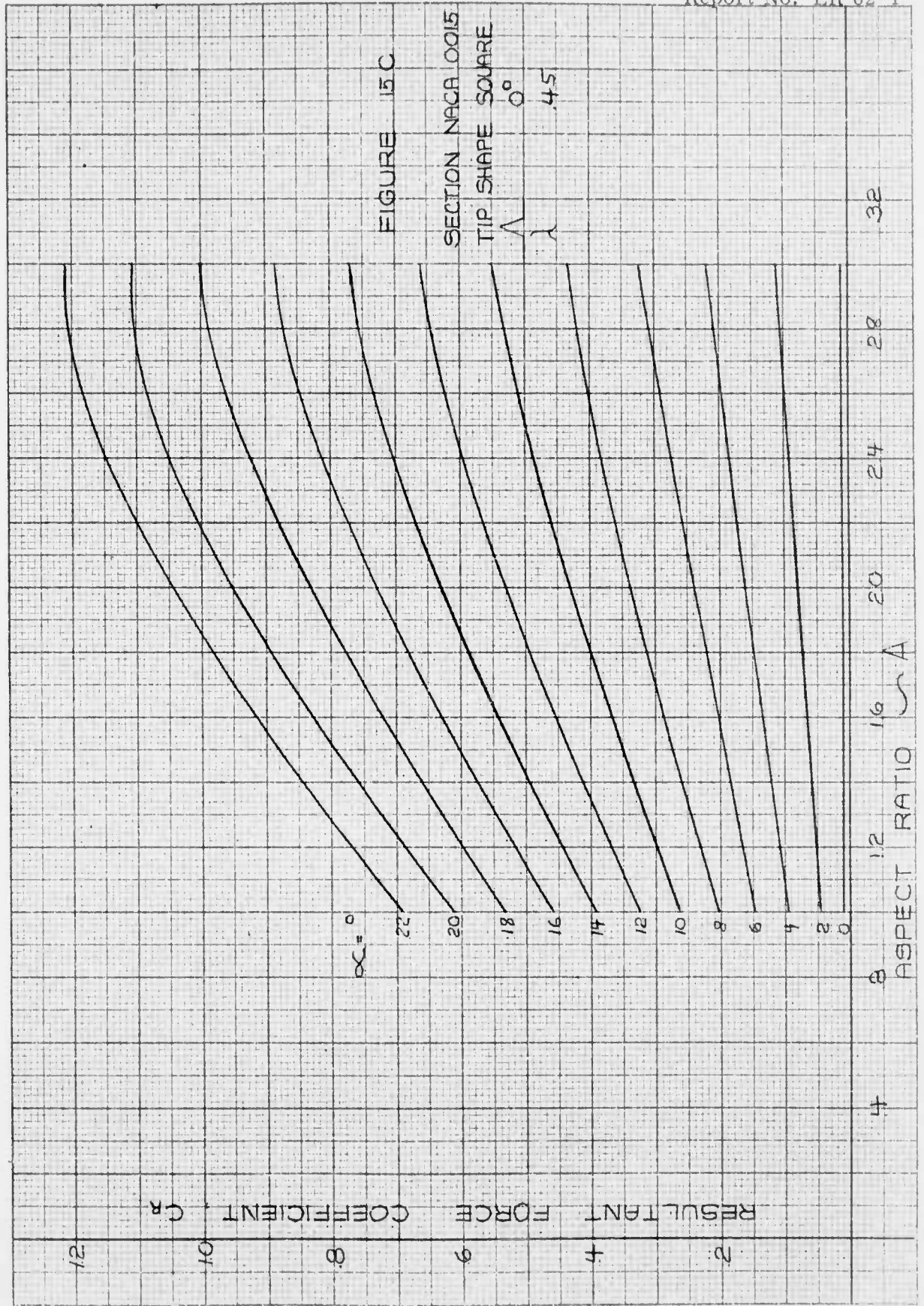


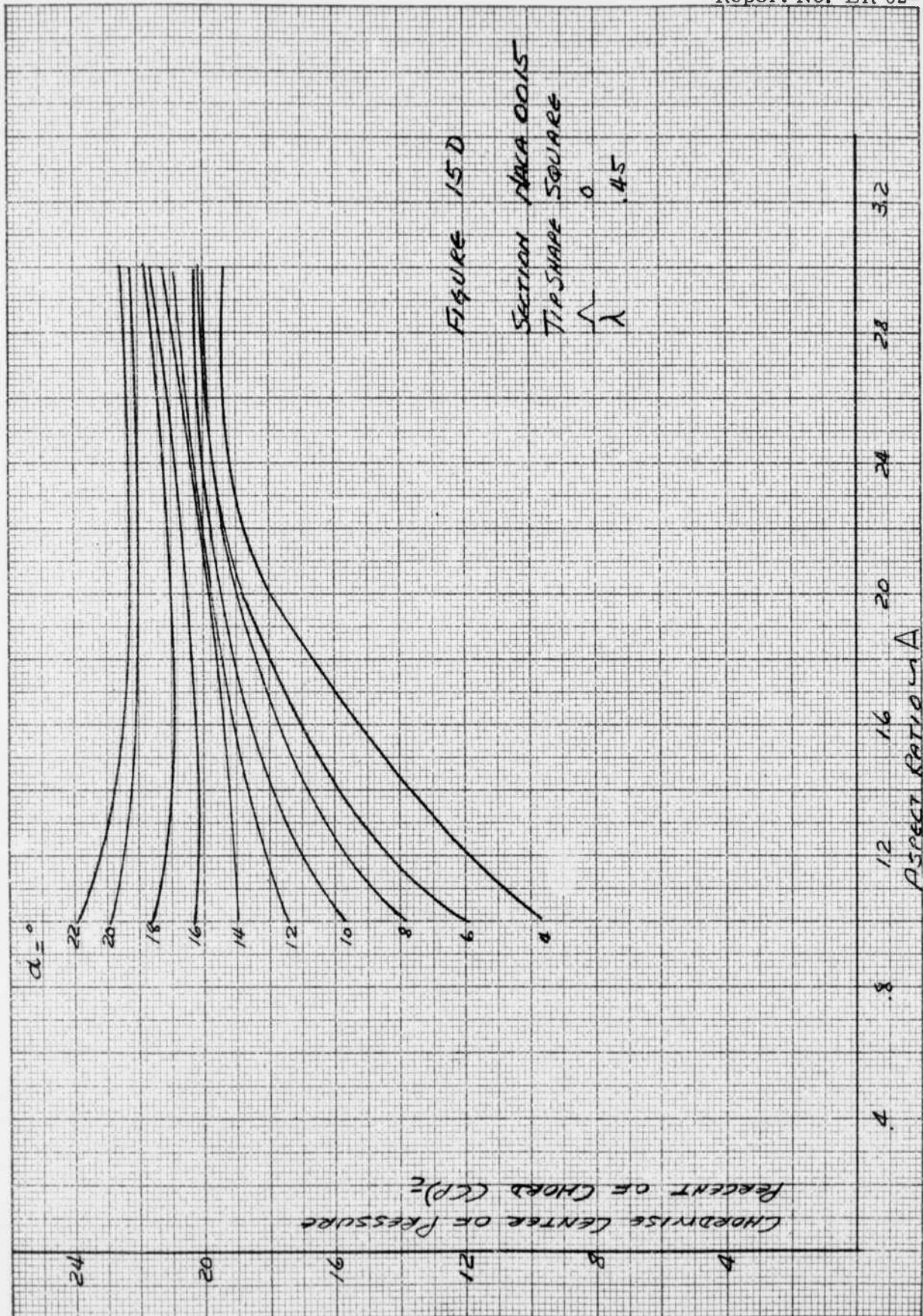


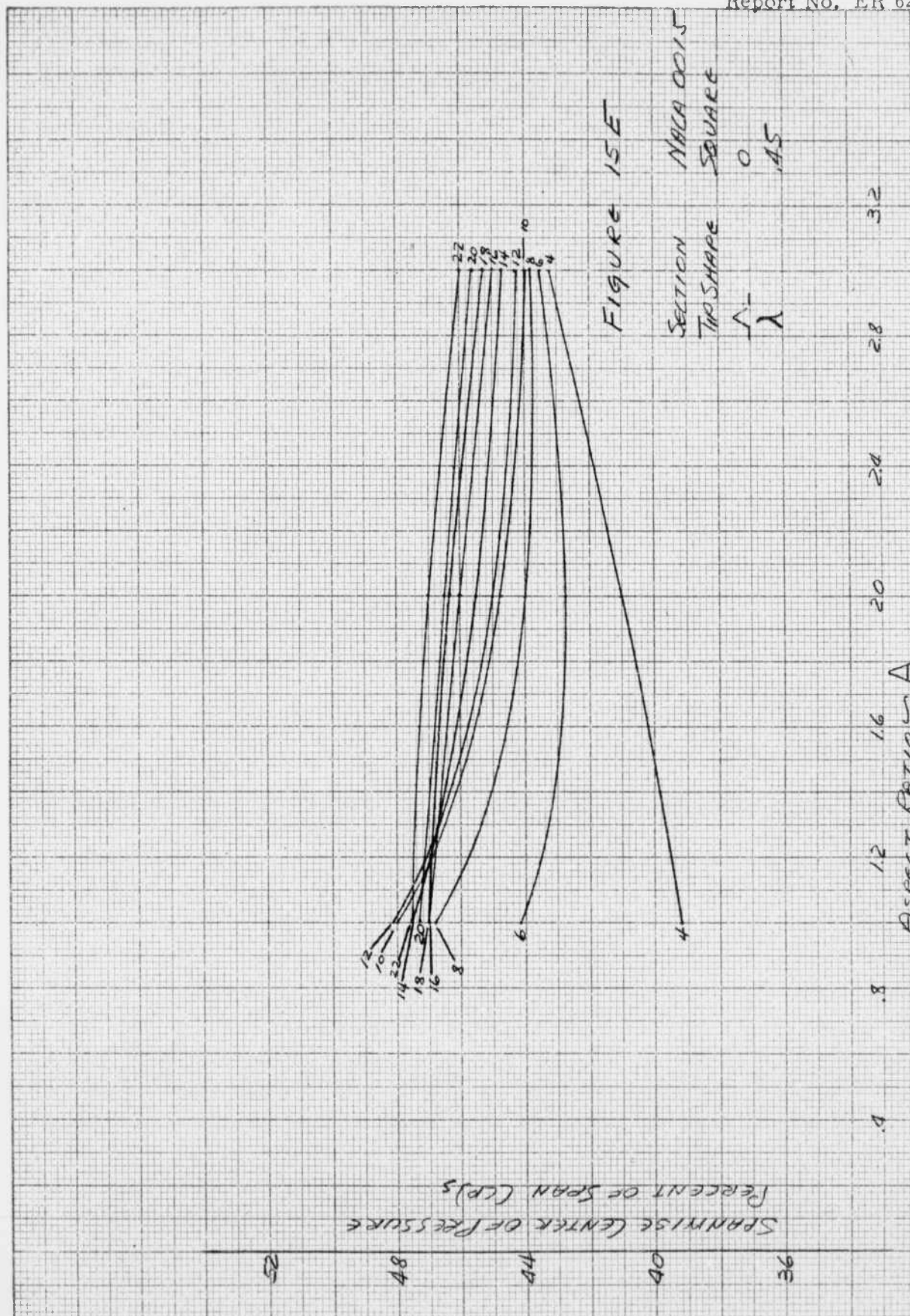


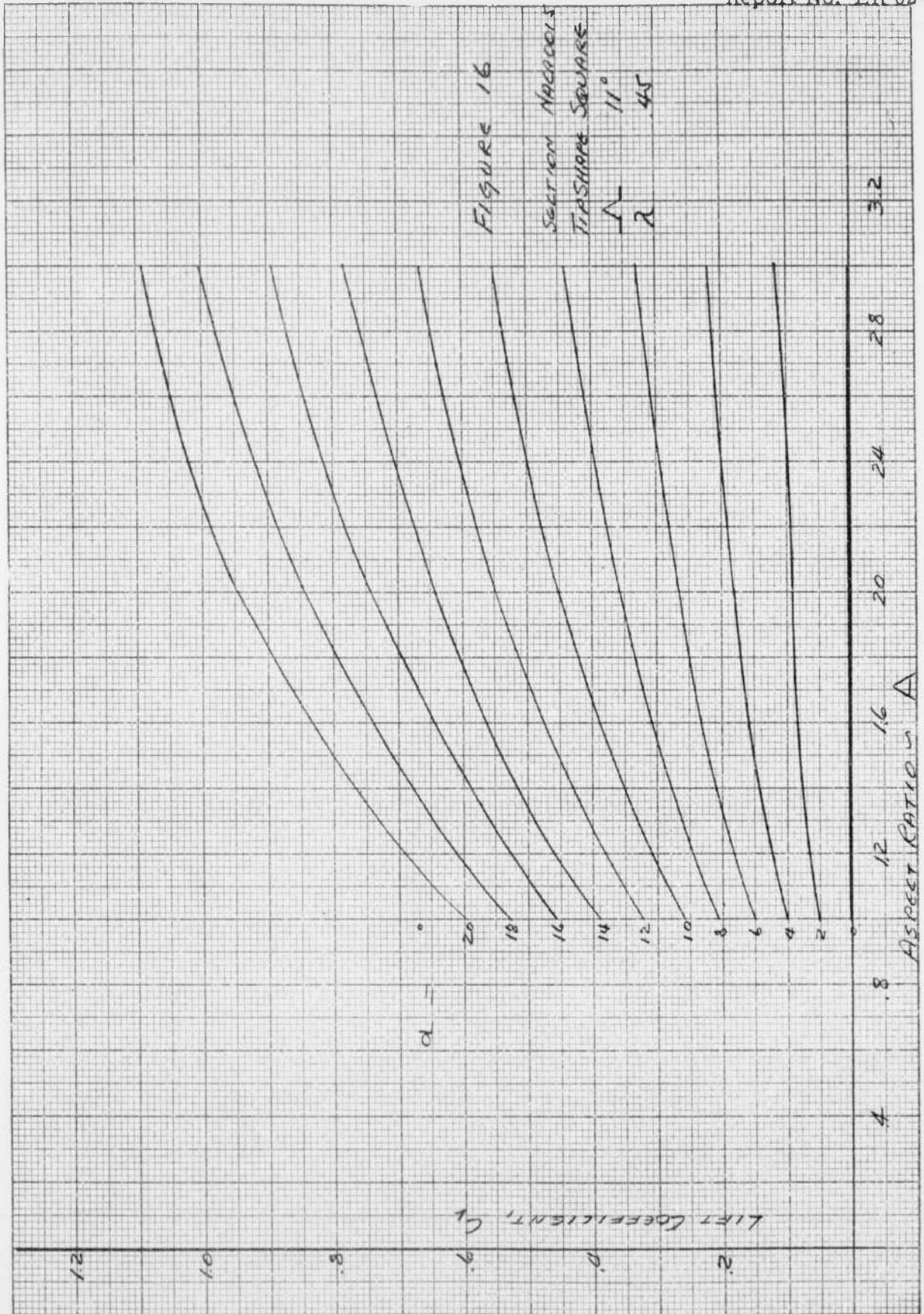


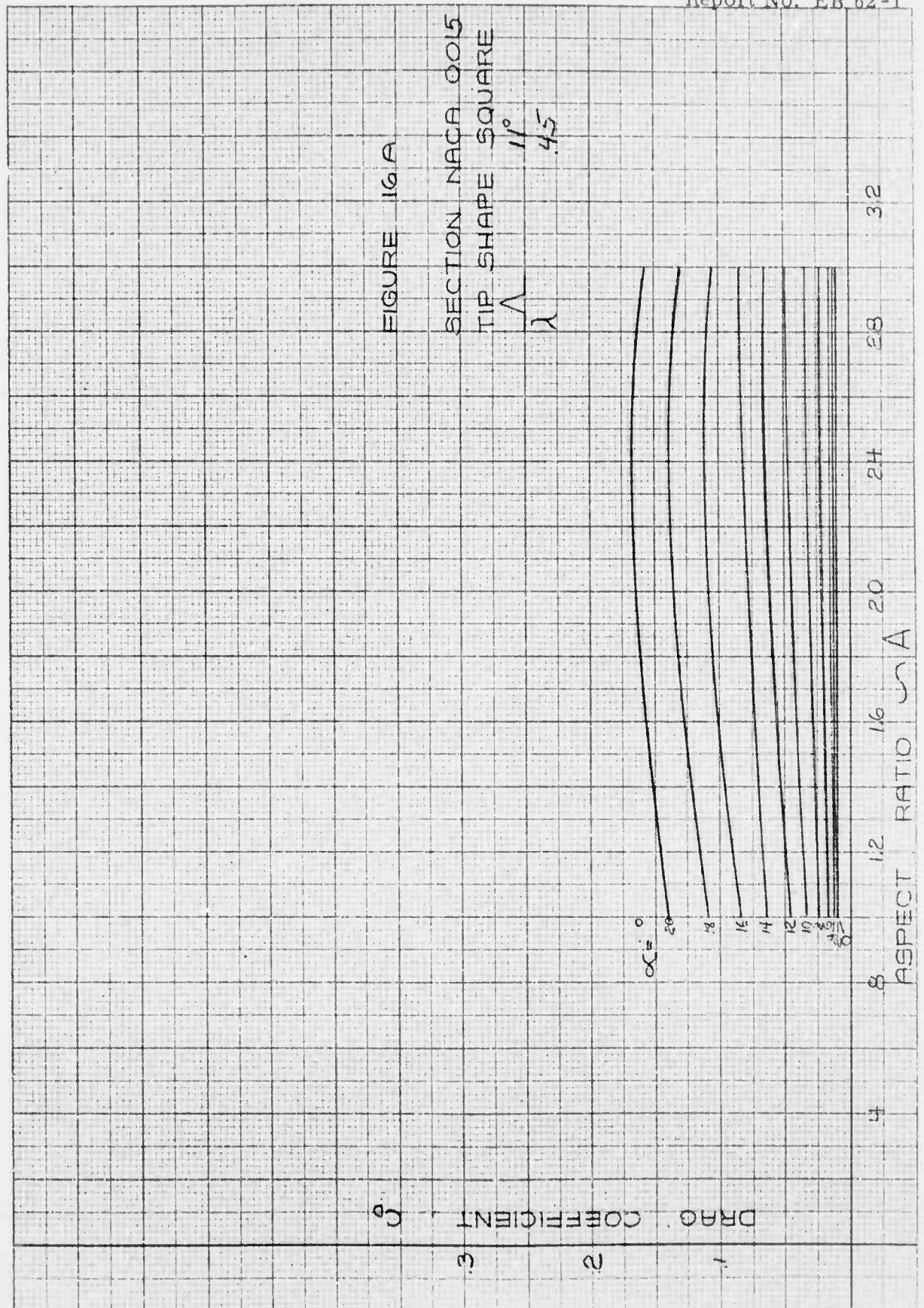


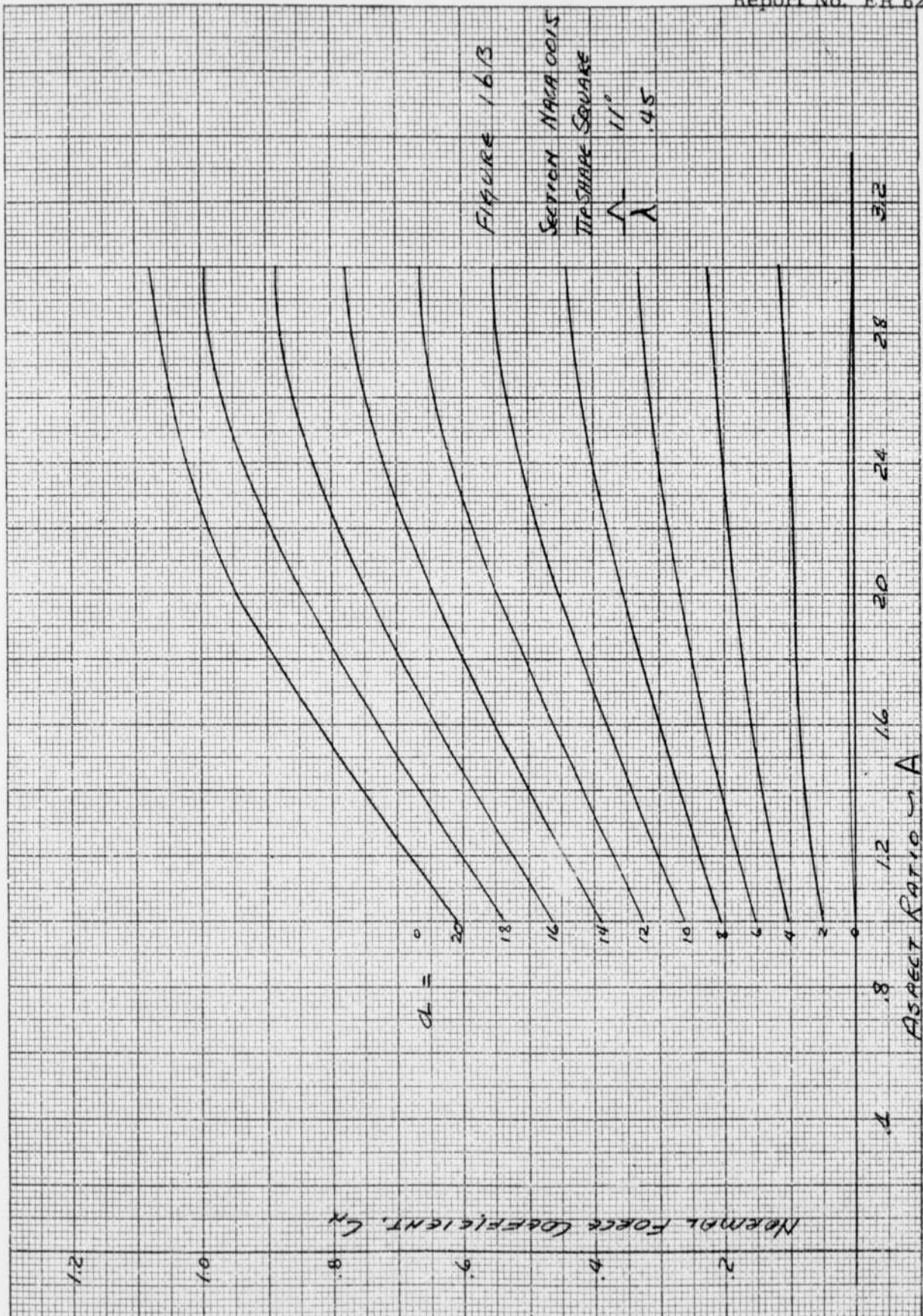


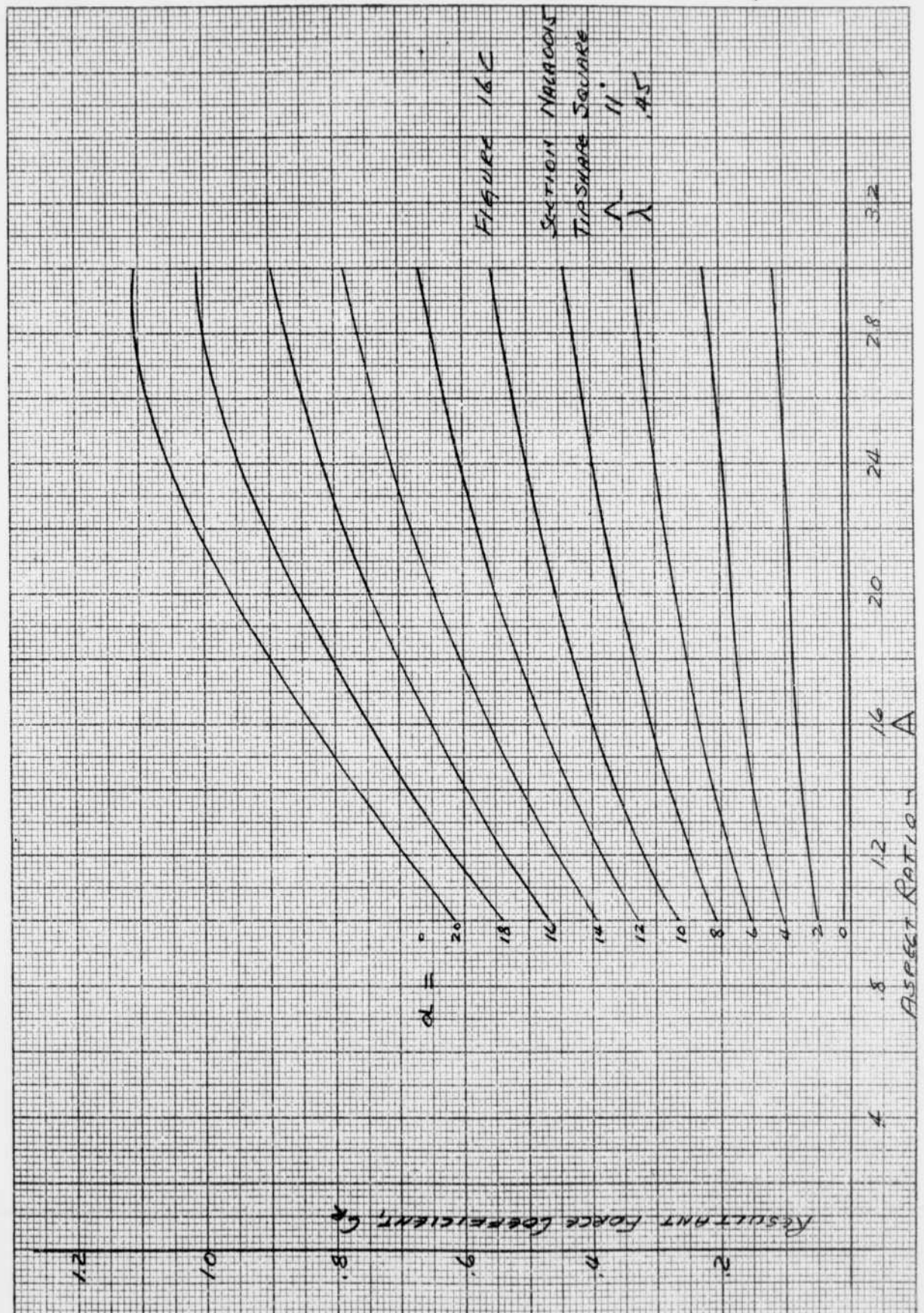


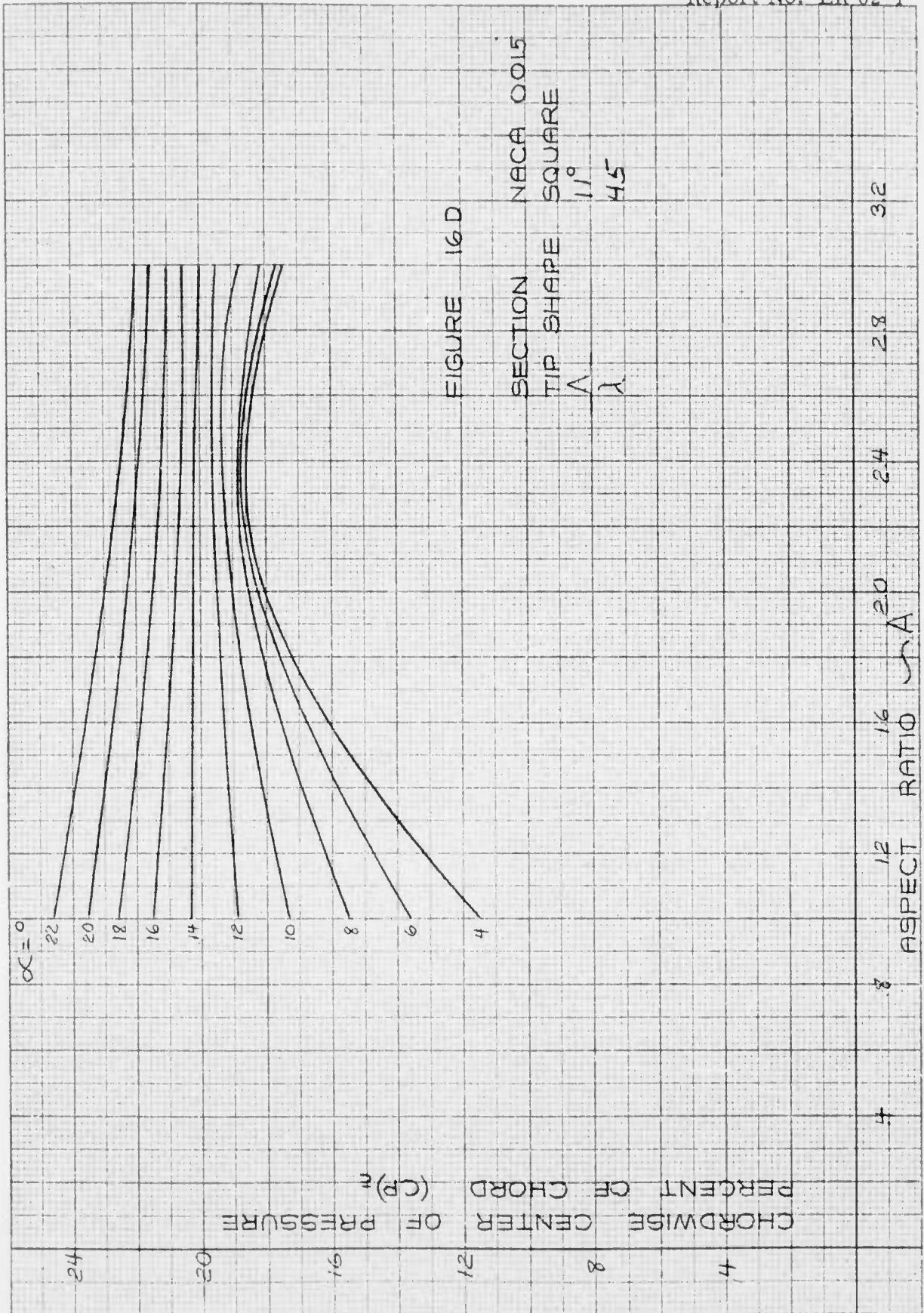


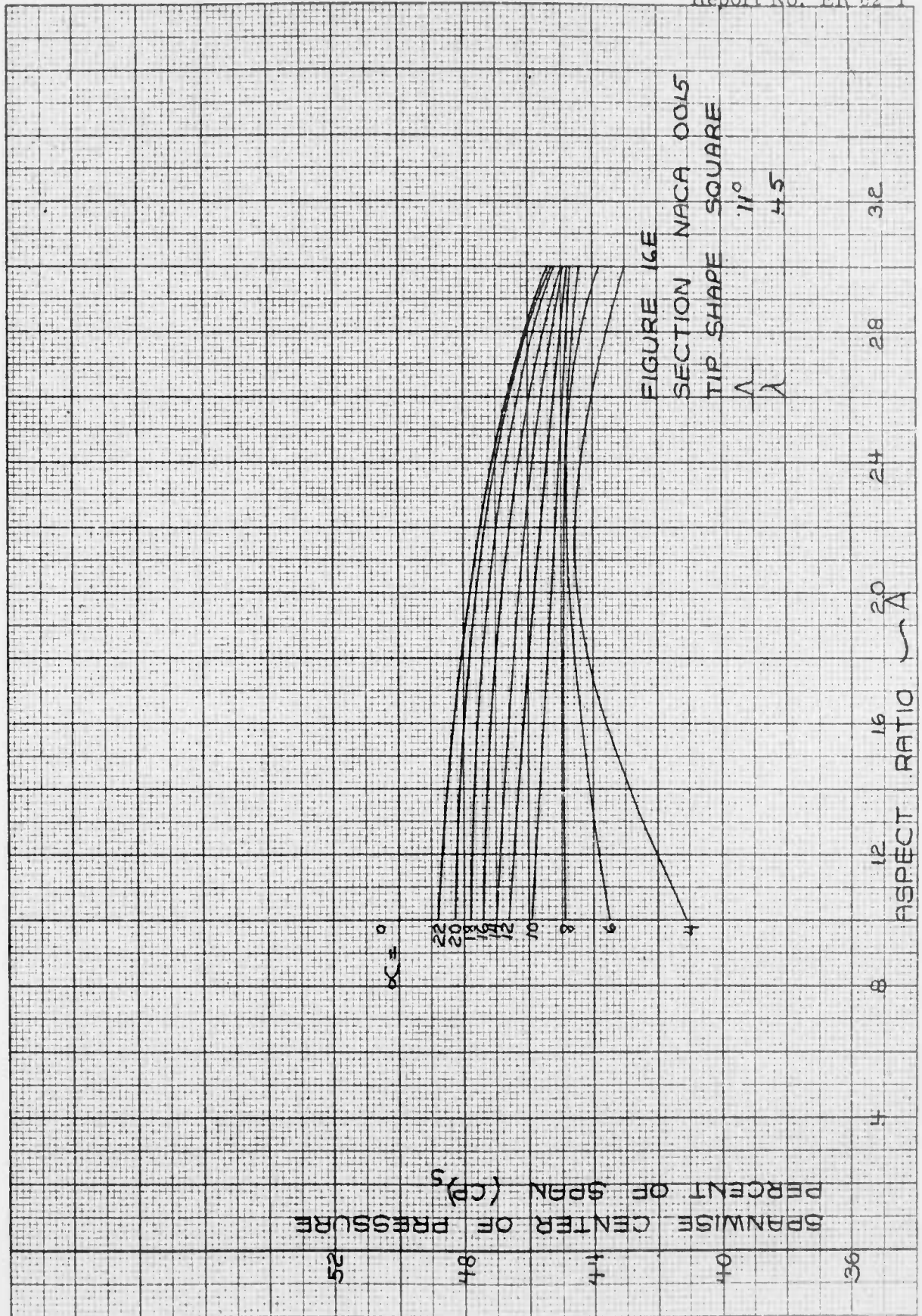


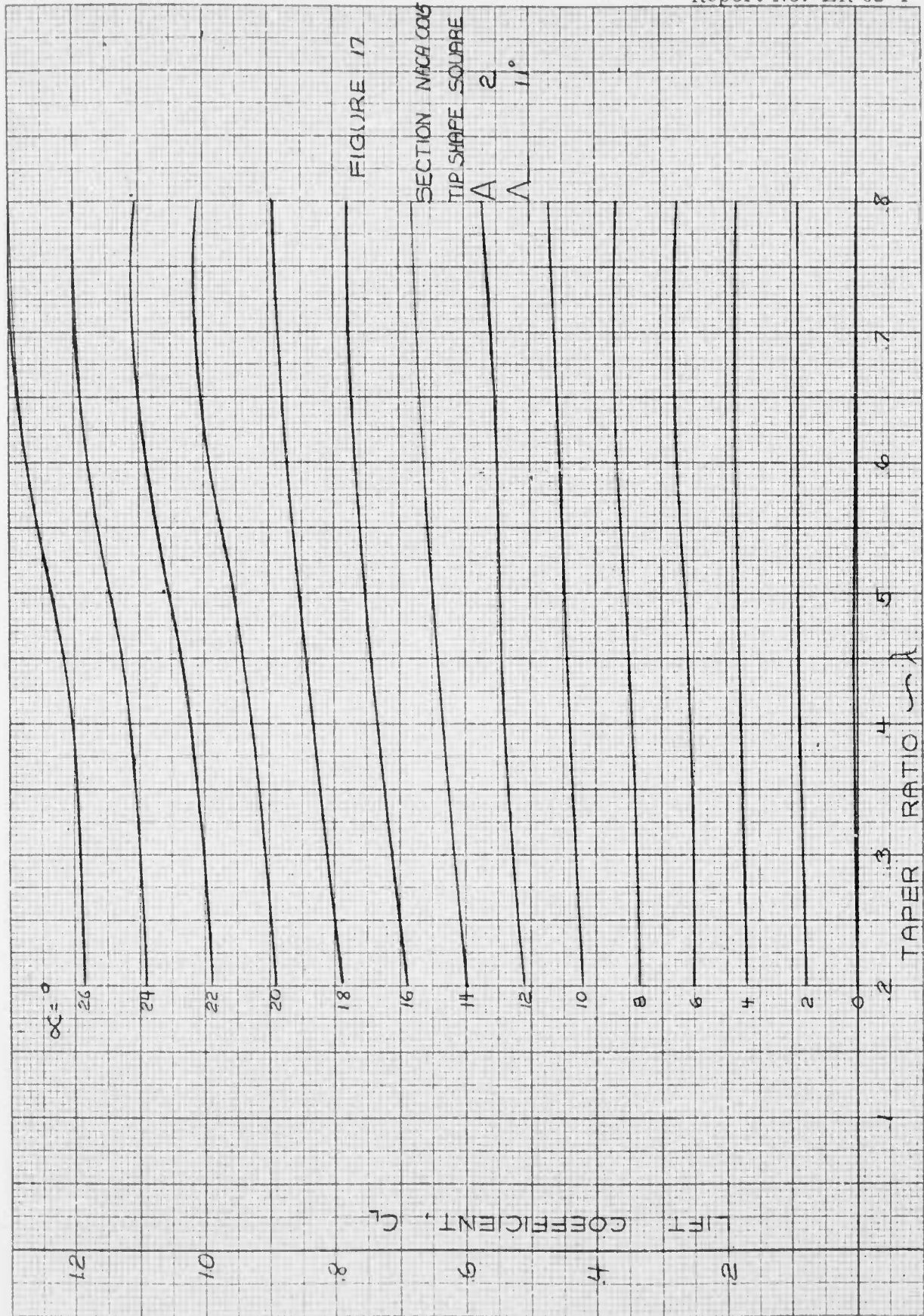


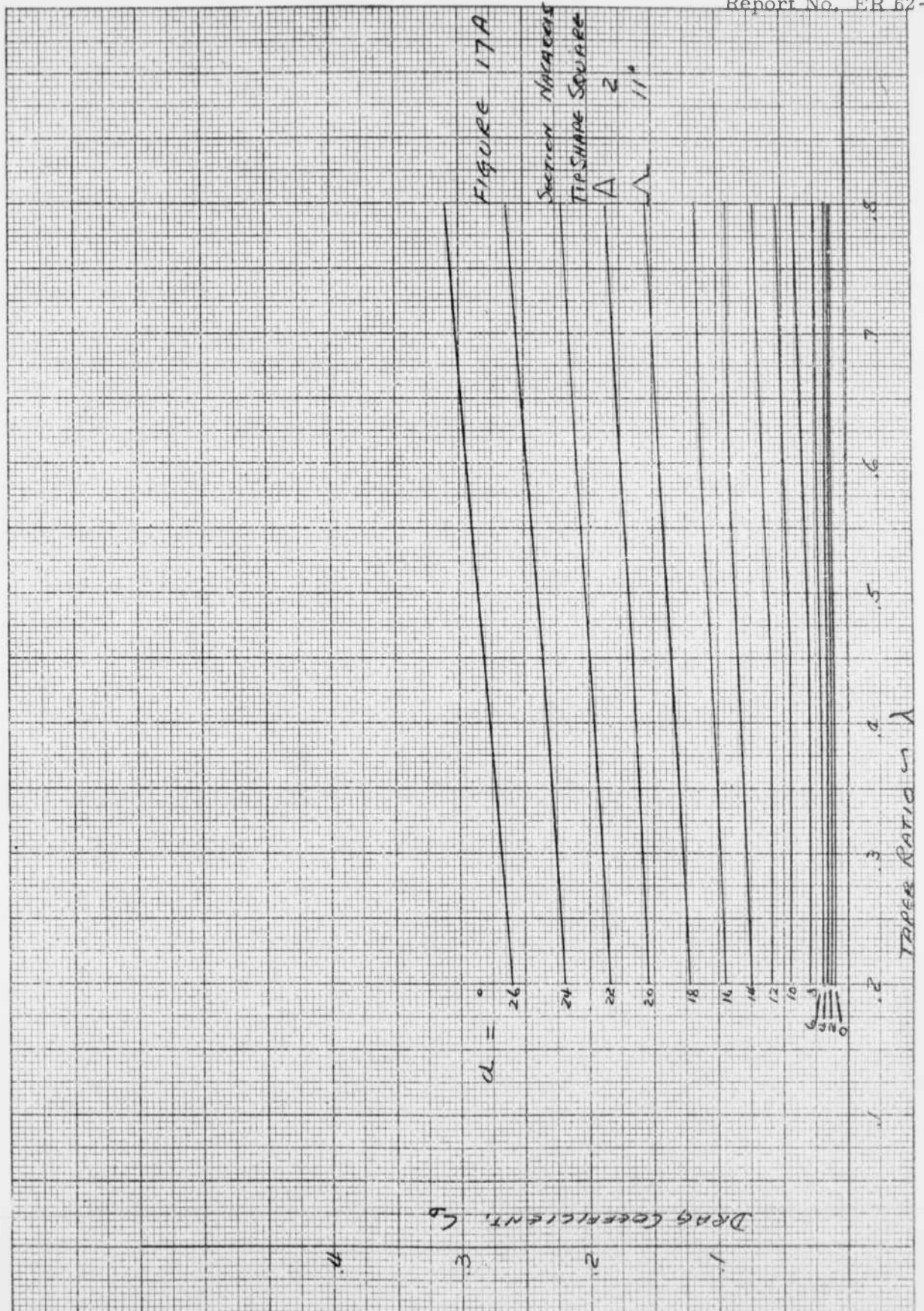


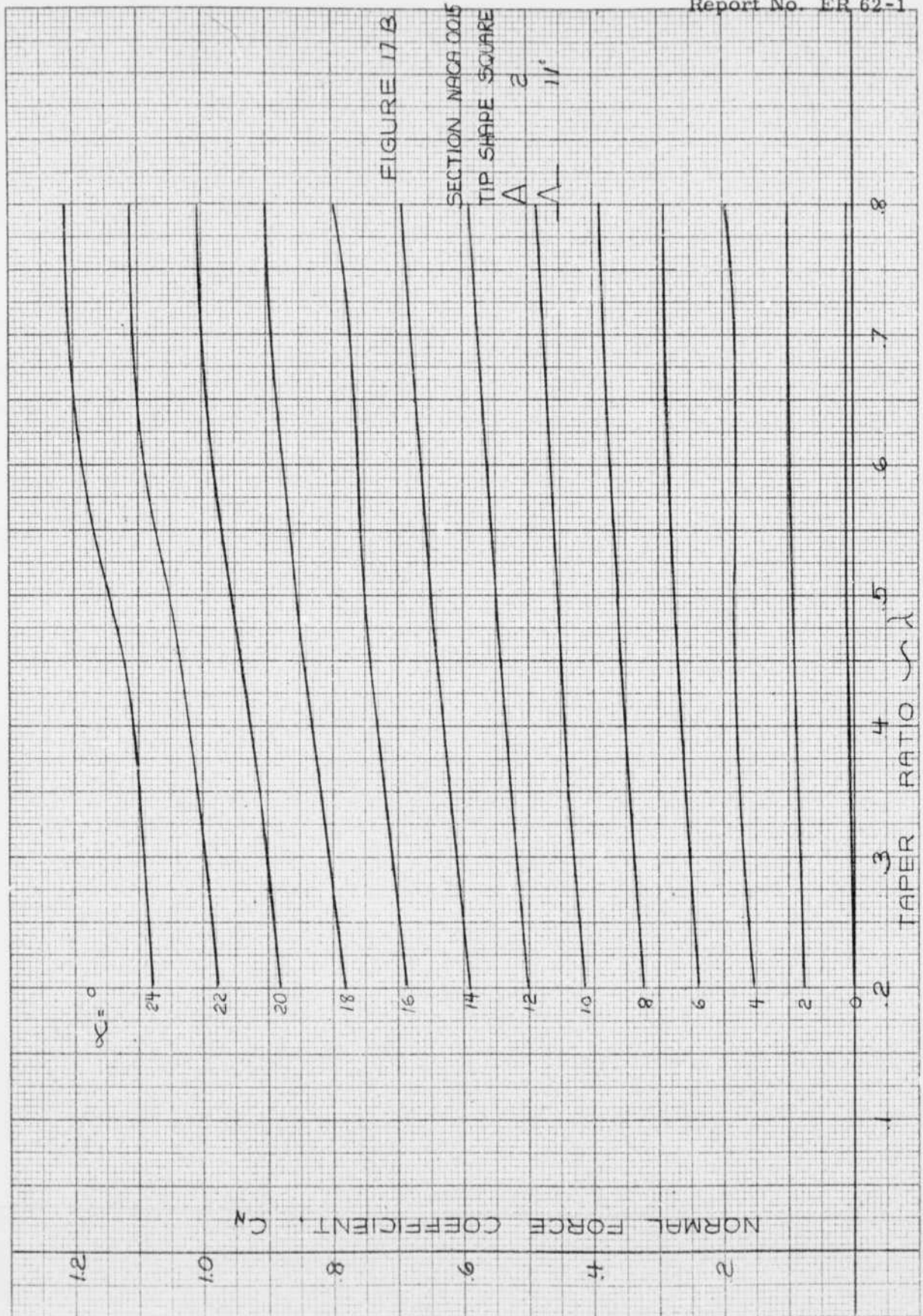


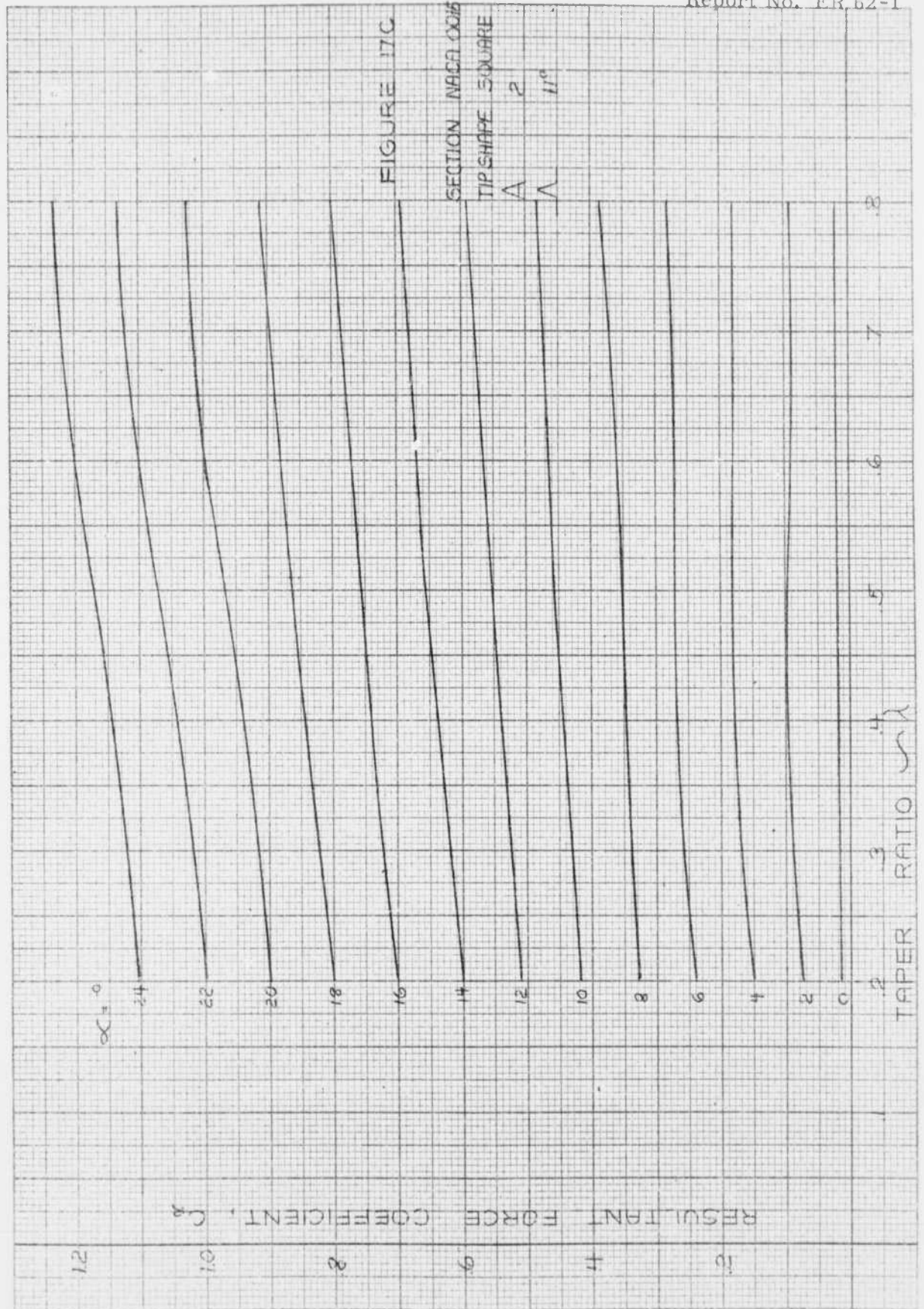


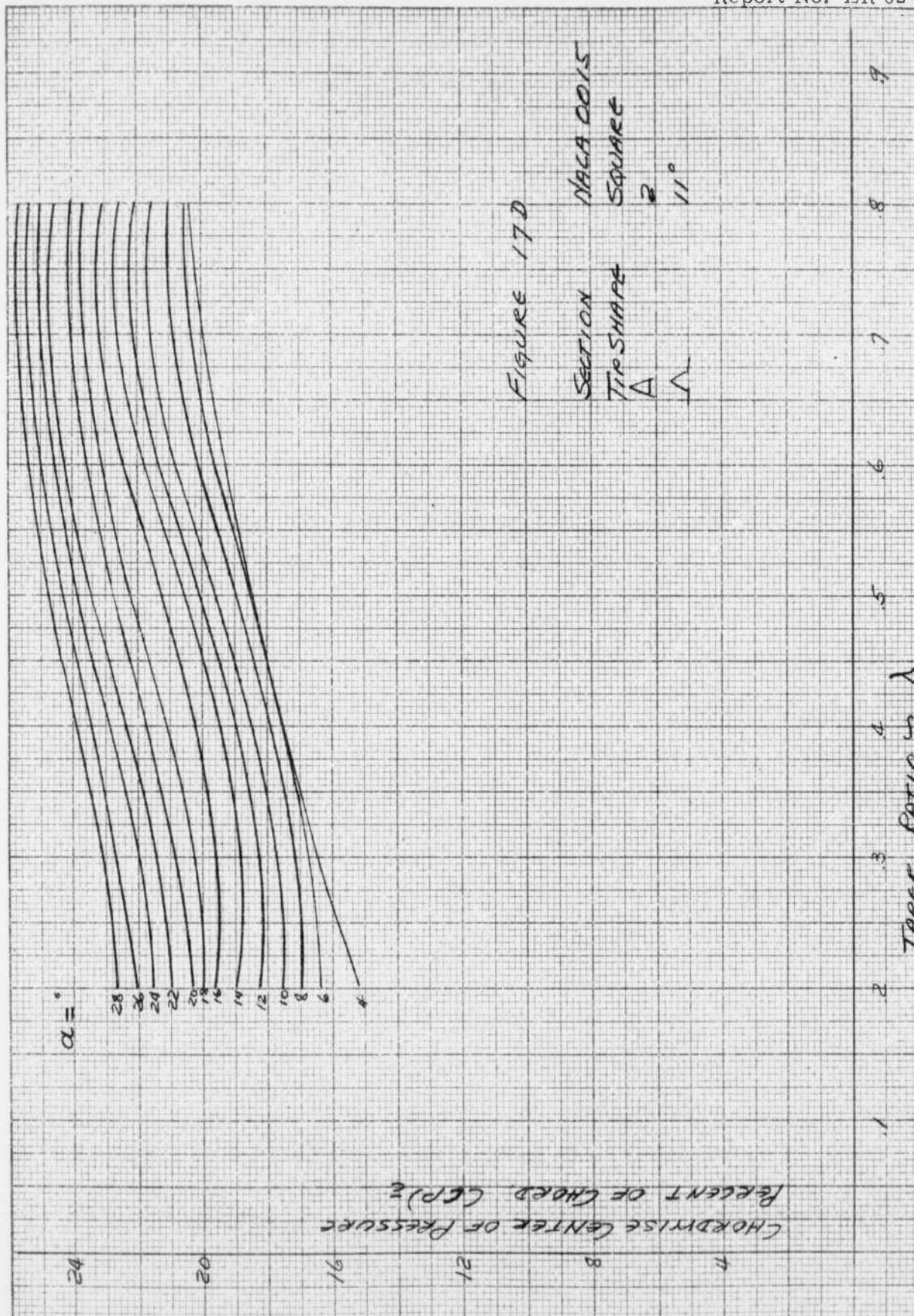












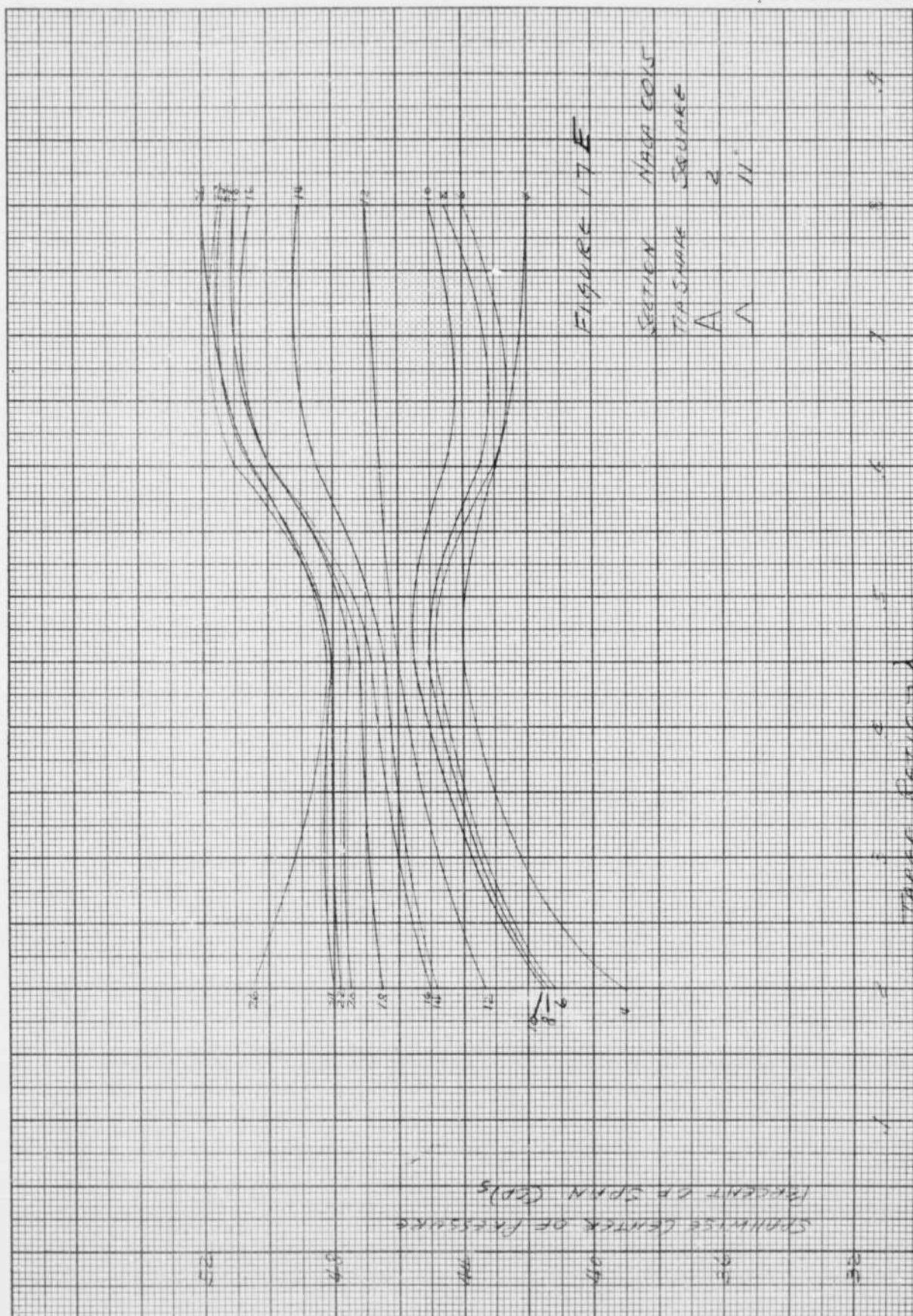


FIGURE 18

SECTION NACA CC15

TIP SHAPE FAIRED

λ — 8
 λ .45

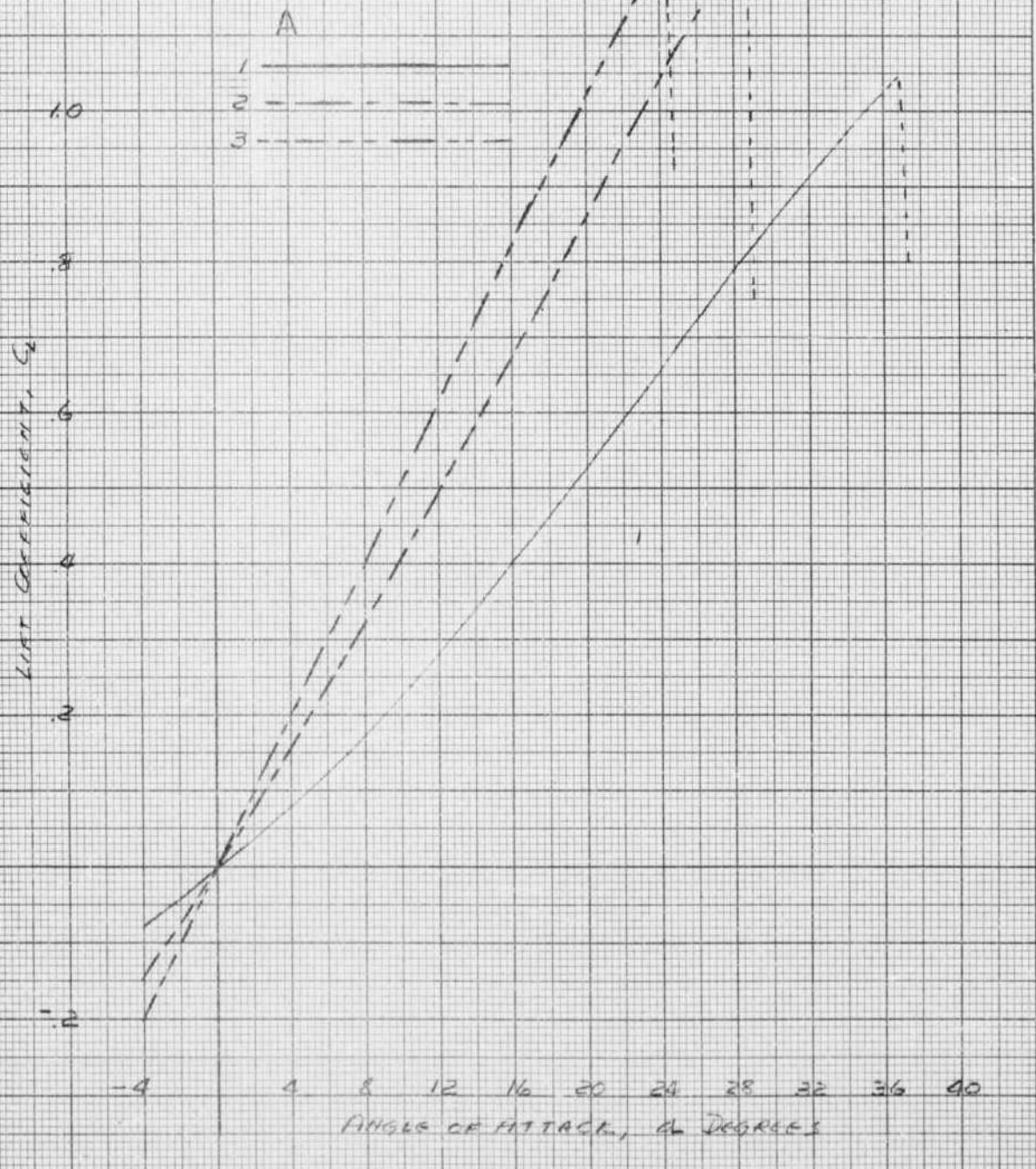


FIGURE 18A

SECTION NACA
TIP SHAPE FAIRED
— 8°
45

7

A

1 —————
2 - - - - -
3 - - - - -

6

5

5

4

4

3

3

2

2

1

1

0

0

0

0

0

0

0

DRAG COEFFICIENT, C_D

-4

4

8

12

16

20

24

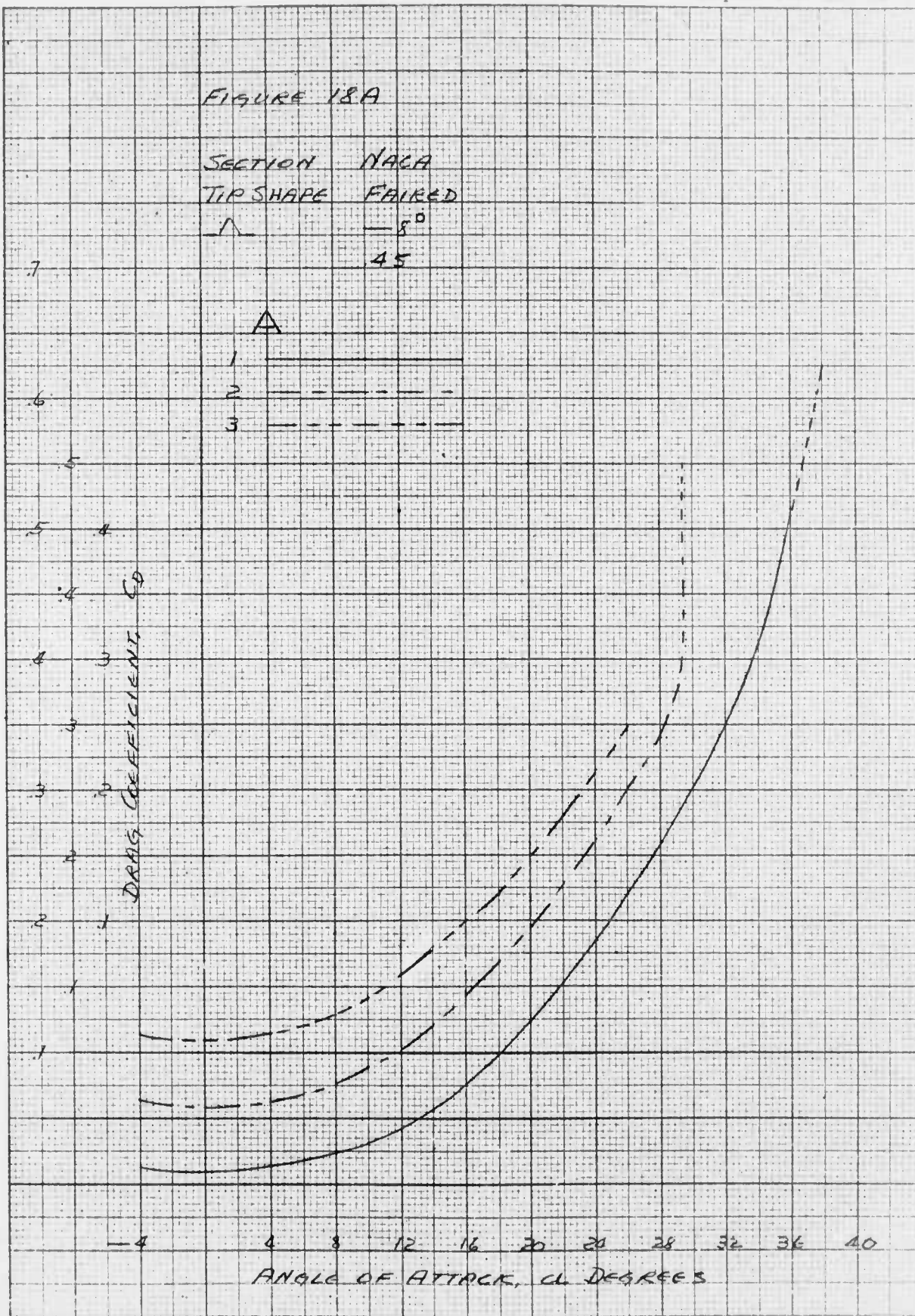
28

32

36

40

ANGLE OF ATTACK, α DEGREES



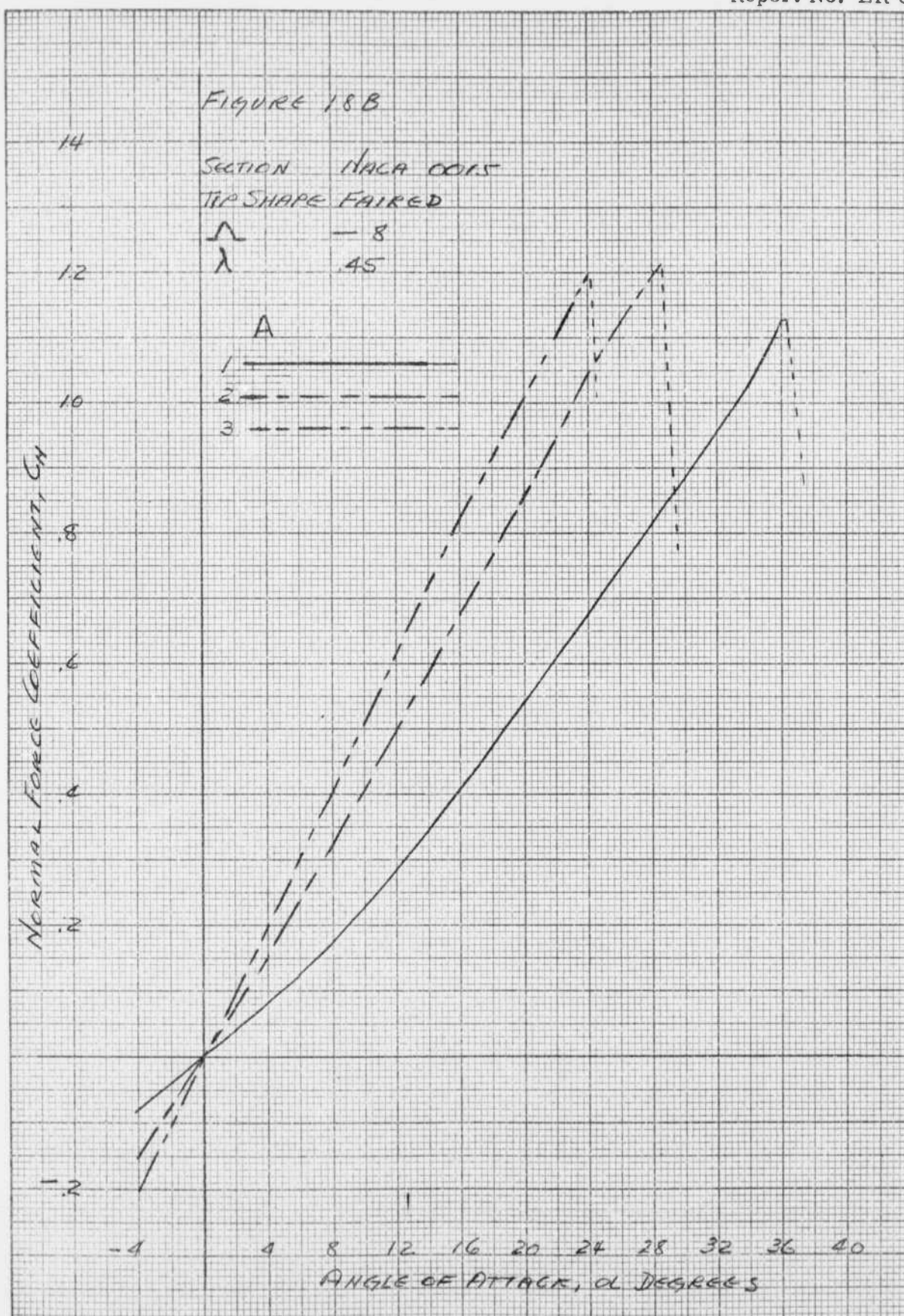


FIGURE 18C

SECTION NACA 0015
TIP SHAPE FAIRED
 Λ - 8
 λ .45

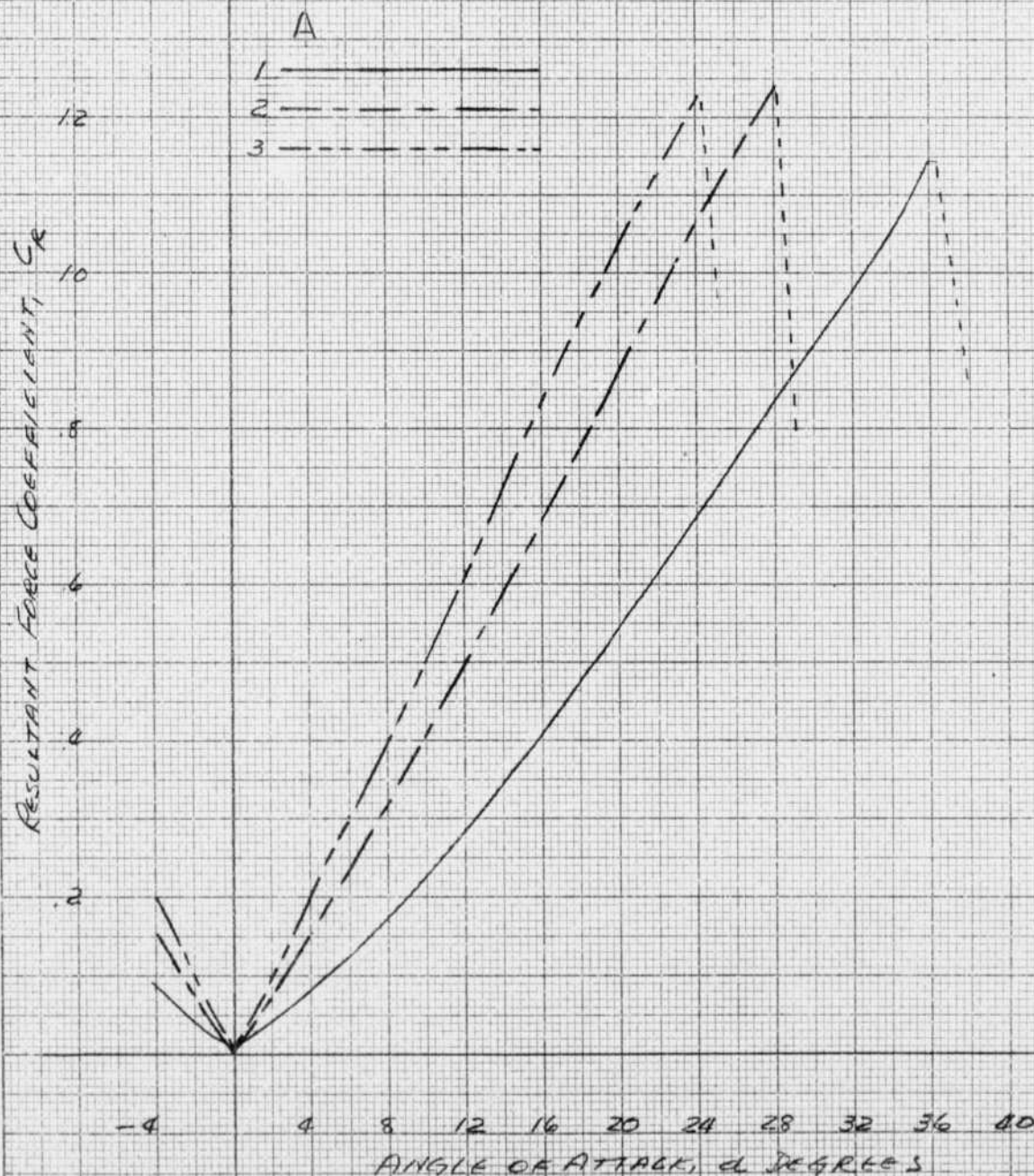


Figure 18D

SECTION	WAVELENGTH
710-7400	7100
λ	8
λ	45

4

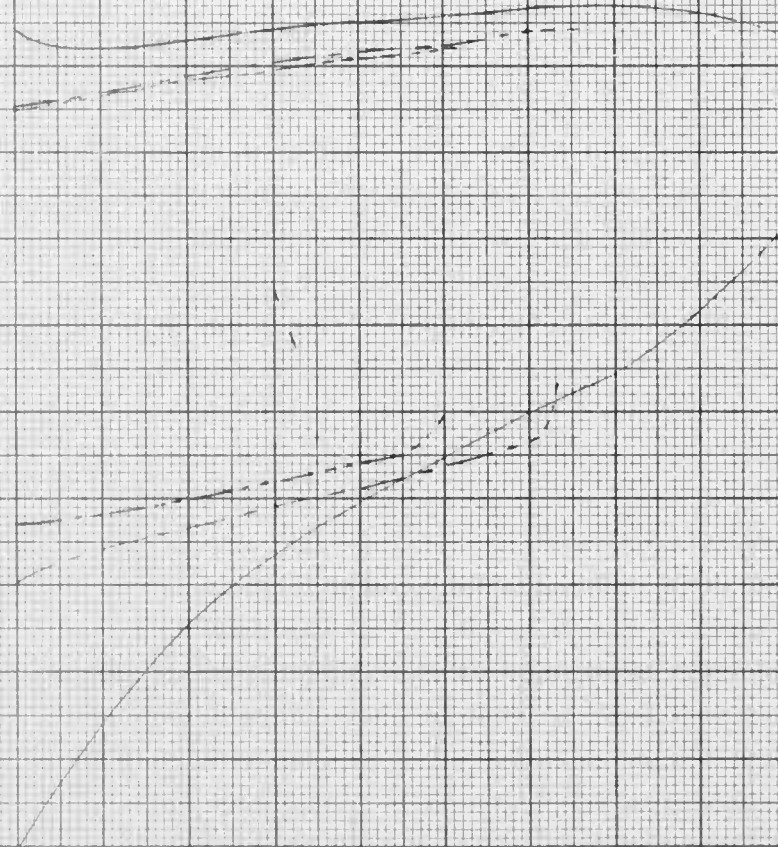
1

2

3

WAVELENGTH (microns)

7100 7200 7300 7400 7500 7600 7700 7800 7900 8000 8100 8200 8300 8400 8500 8600 8700 8800 8900 9000 9100 9200 9300 9400 9500 9600 9700 9800 9900 10000



ANGLE OF ATTACK, IN DEGREES

FIGURE 19

SECTION NACA 0015
TIP SHAPE FAIRED
 λ 0
 λ .15

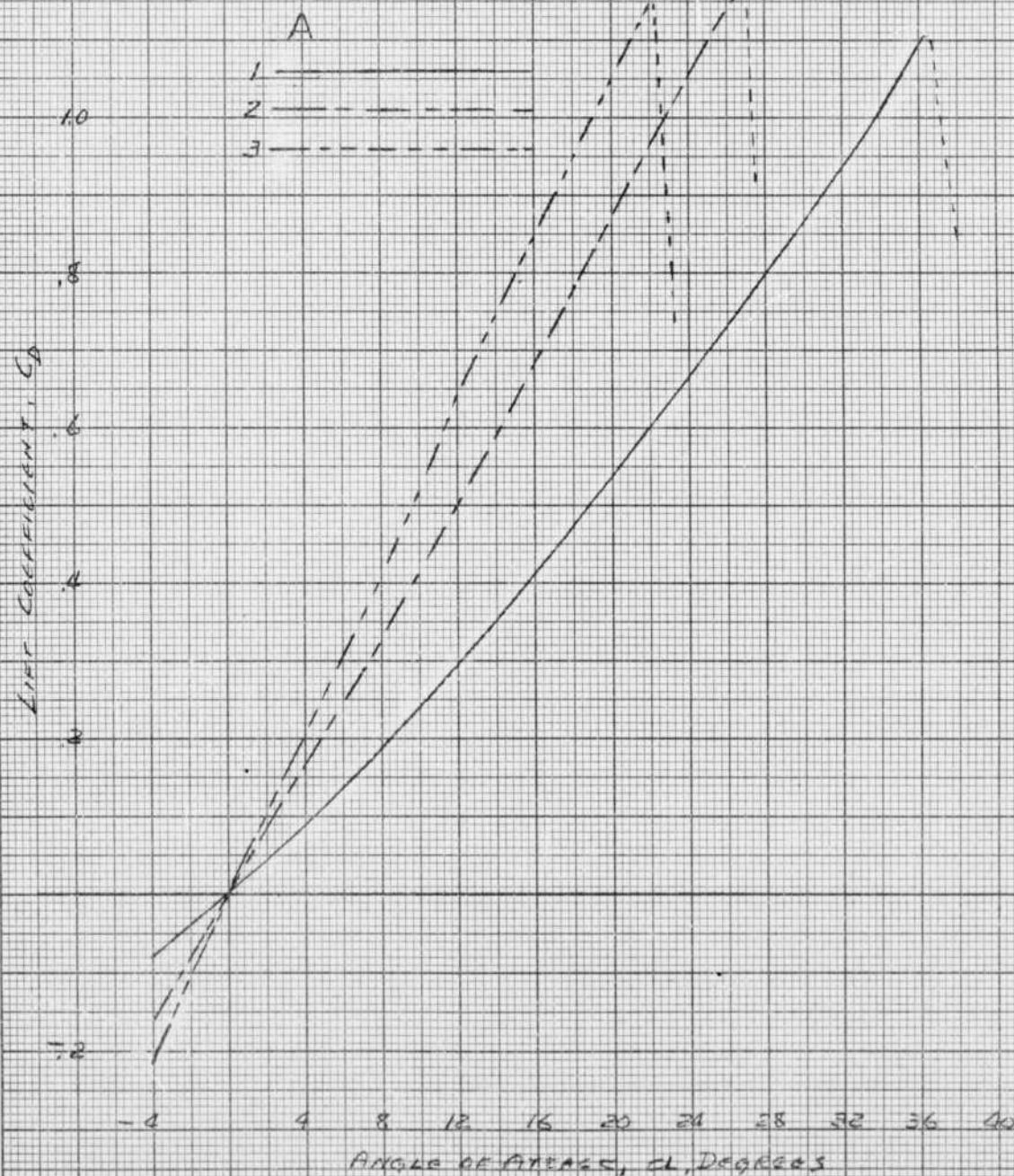


FIGURE 19A

SECTION NACA 6015
TIP SHAPE FINED
 Λ 0
 λ .45

A
1 —————
2 - - - - -
3 - - - - -

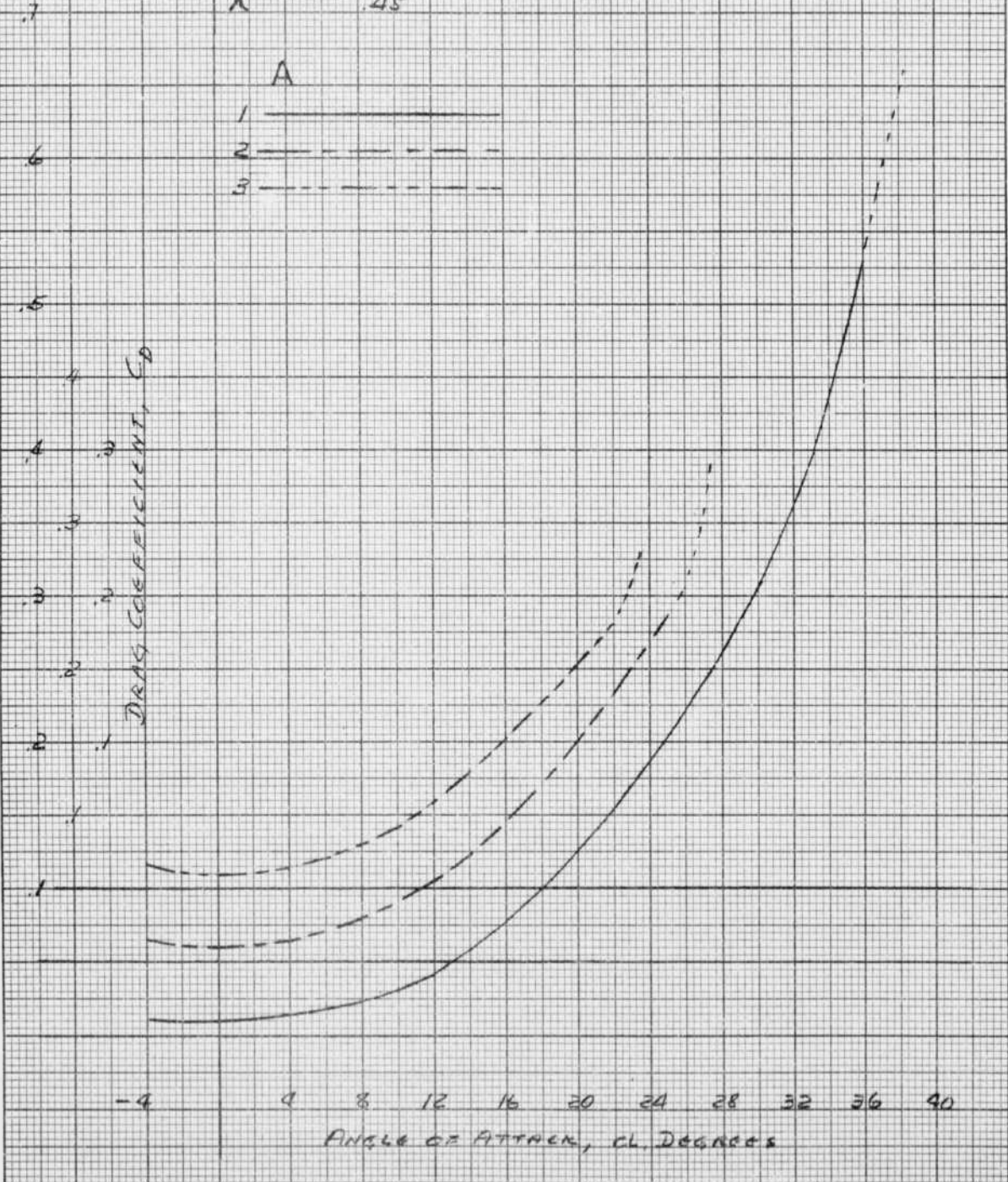


FIGURE 19B

SECTION NACA 0015

TIP SHAPE FAIRED

Λ 0
 λ .45

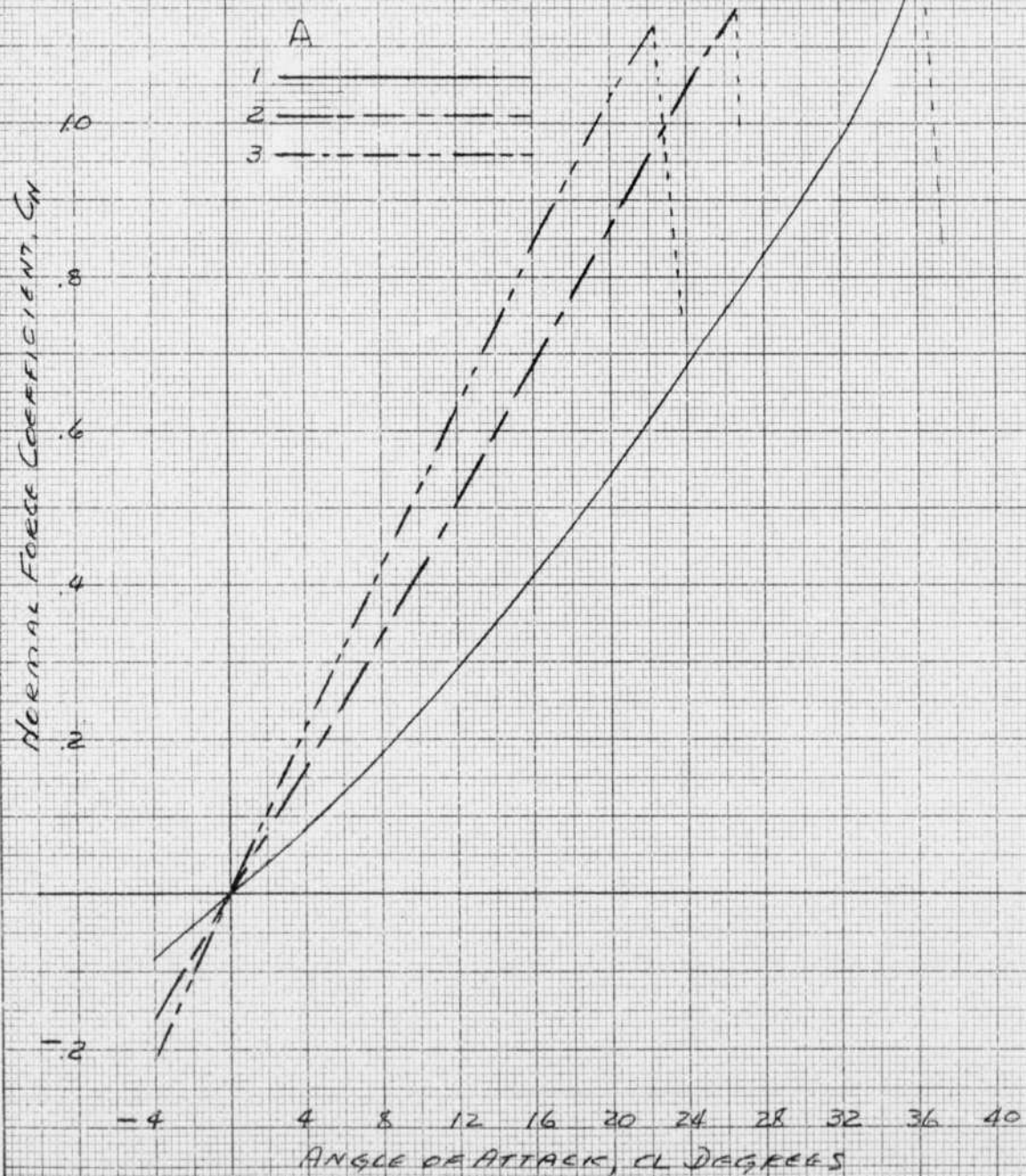


FIGURE 19C

SECTION NACA 0015
TIP SHAPE FAIRED

Δ 0
 λ .45

A

- 1 —————
- 2 - - - - -
- 3 - - - - -

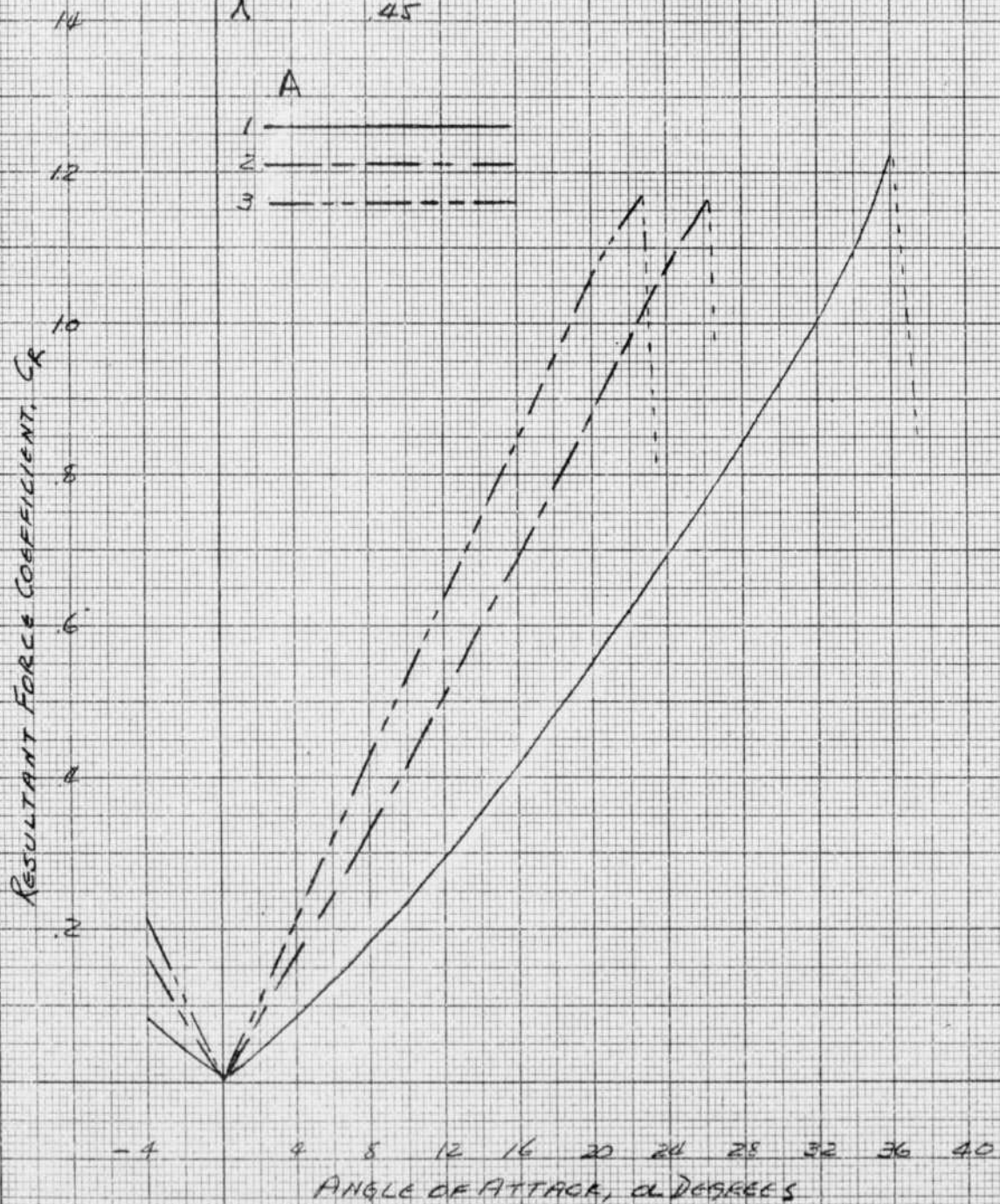


FIGURE 19D

SECTION	NACA 0015
TIP SHAPE	FAIRED
λ	0
λ	.45

SPANWISE CENTER OF PRESSURE
PERCENT OF SPAN (C.P.S.)

CHORDWISE CENTER OF PRESSURE
PERCENT OF CHORD (C.P.C.)

-4

4 8 12 16 20 24 28 32 36 40
ANGLE OF ATTACK, α DEGREES

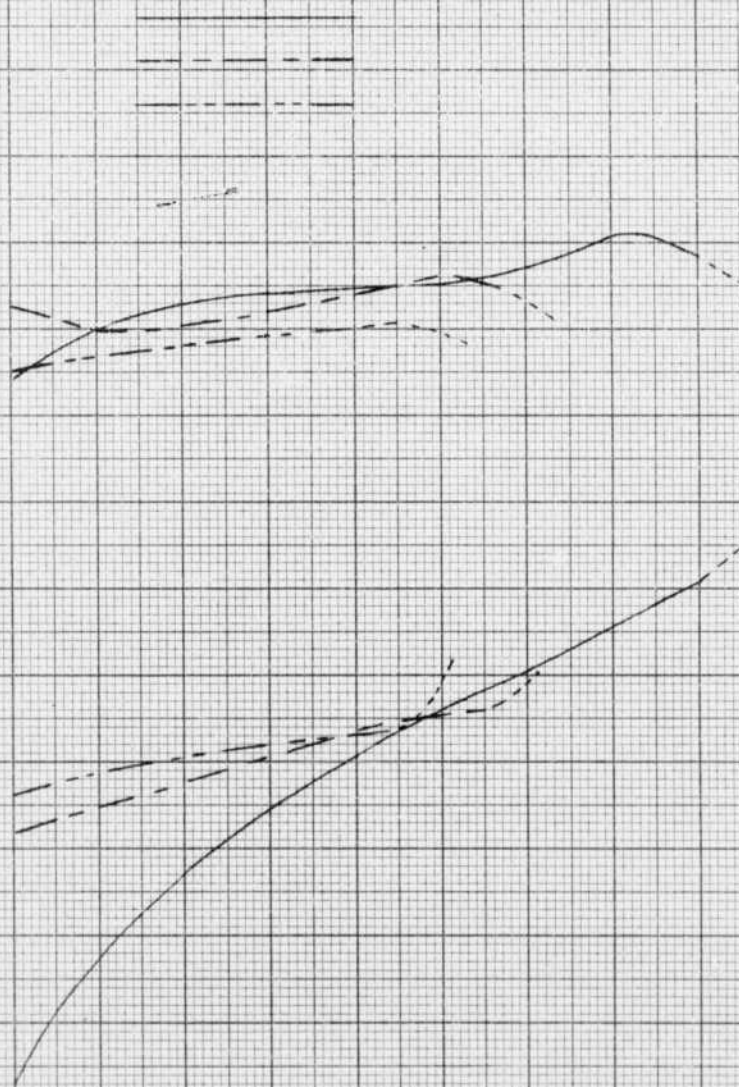


FIGURE 20

SECTION NACA0011
TIP SHAPE FAIRER

Λ 11
 λ .45

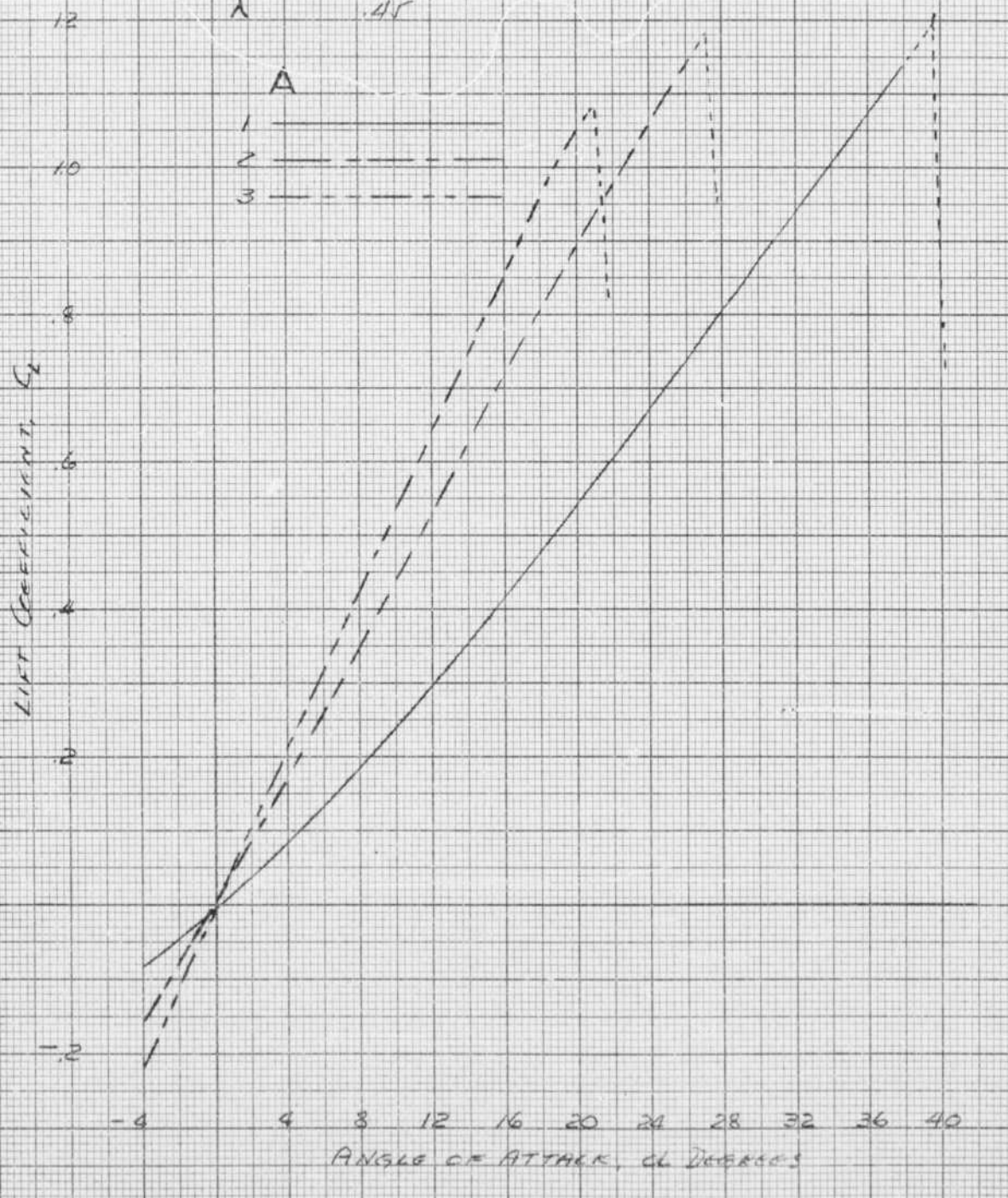


FIGURE 20A

SECTION NACA 0015
TIP SHAPE FAIRED

Λ 11
 λ .45

.7

A

1 —————
2 - - - - -
3 - - - - -

.6

.5

.4

.3

.2

.1

.0

.1

.2

.3

.4

.5

.6

.7

-4

4

8

12

16

20

24

28

32

36

40

ANGLE OF ATTACK, α DEGREES

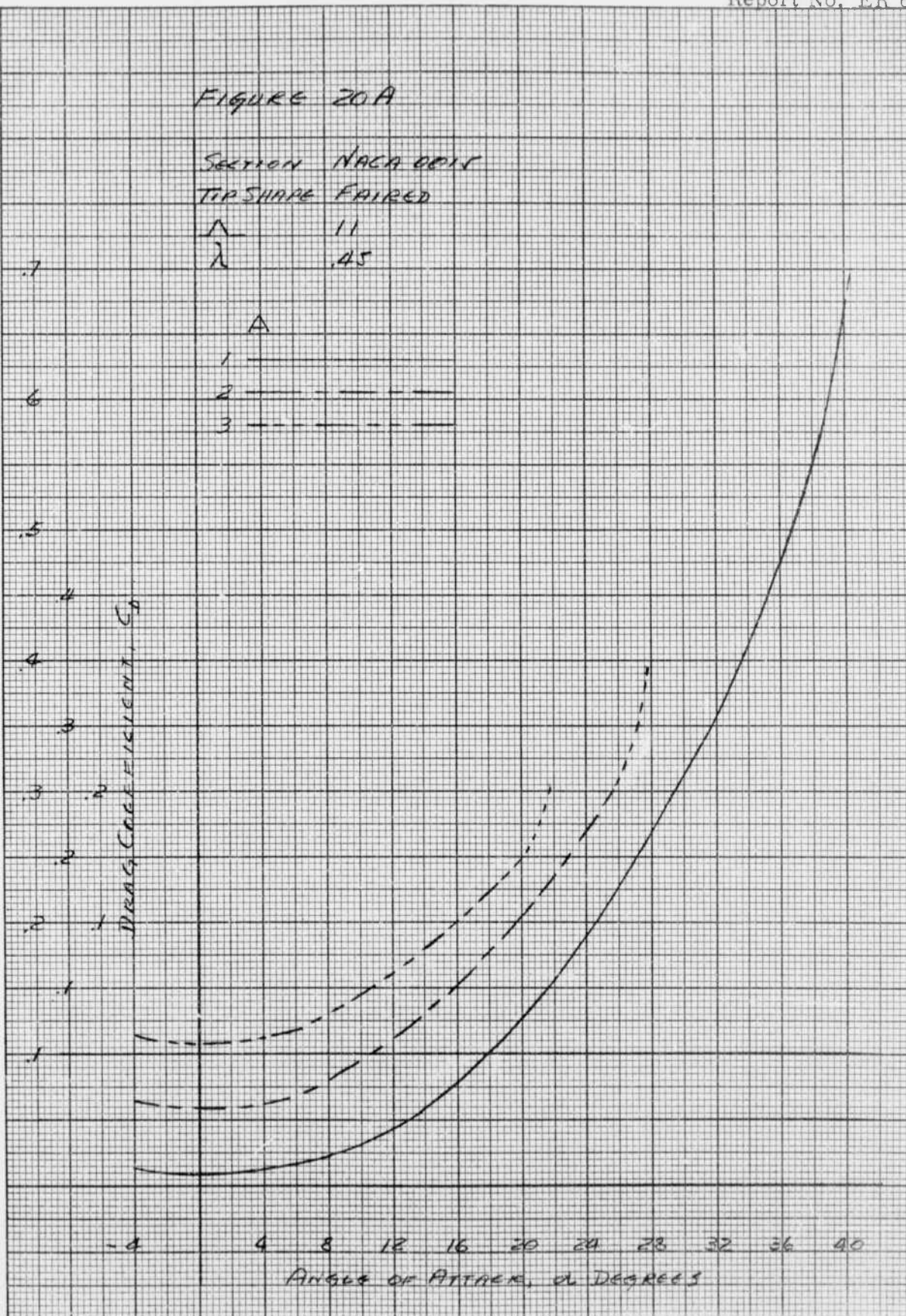


FIGURE 20B

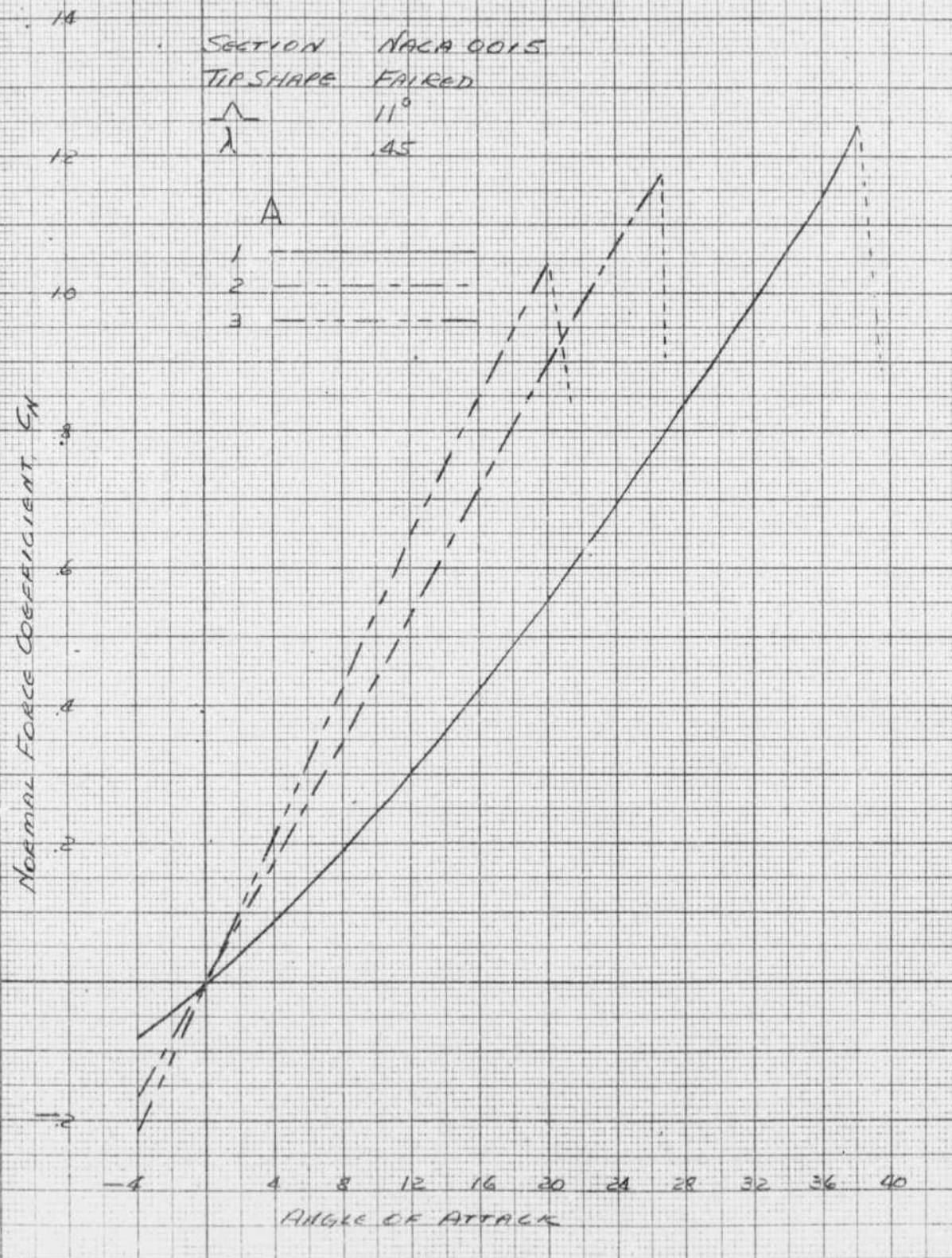


FIGURE 20C

SECTION NACA 0015
TIP SHAPE FAIRED

λ 11
 λ .45

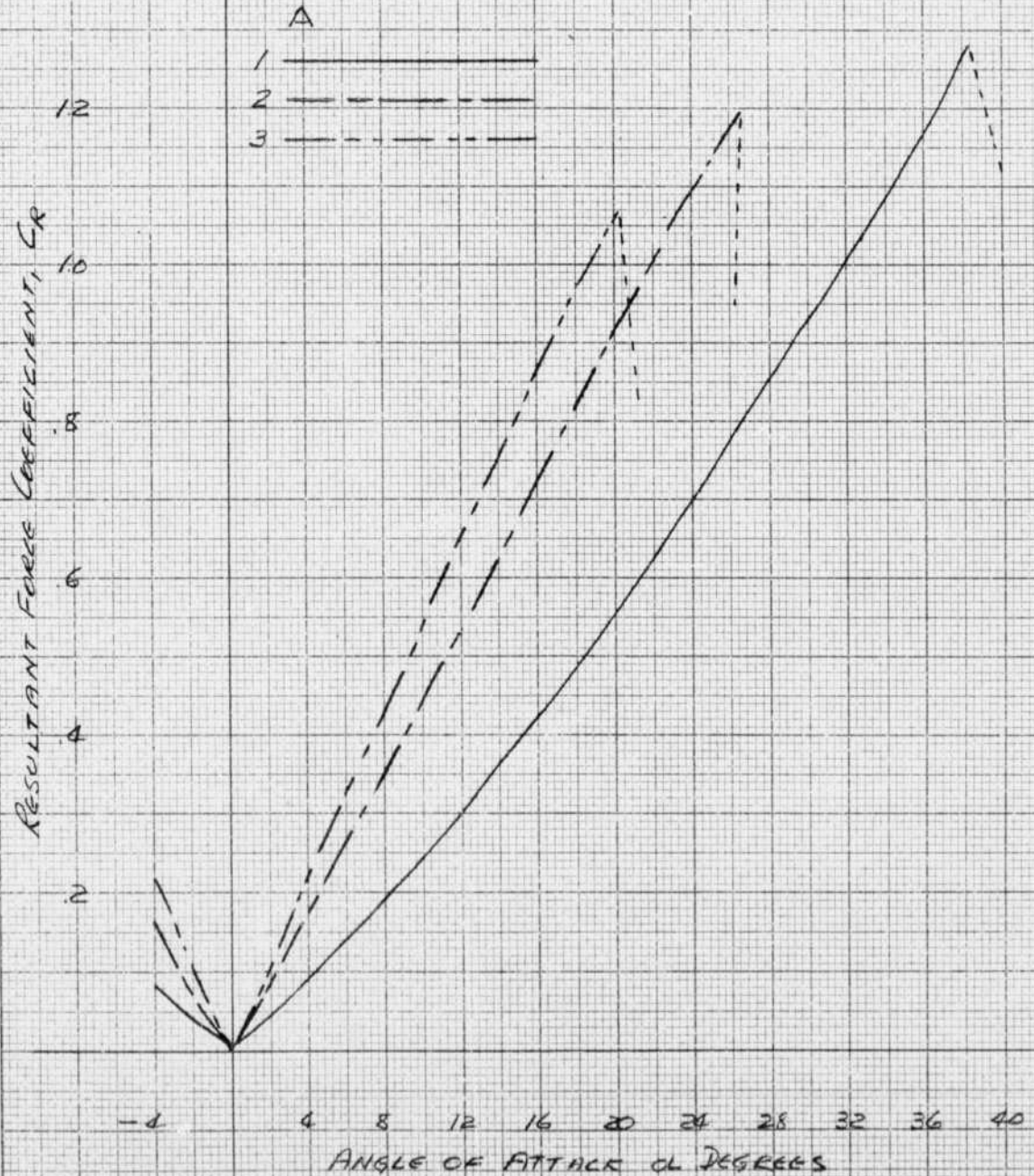


FIGURE 20D

SECTION	NACA 0015
TIP SHAPE	FANDED
Λ	11
λ	45

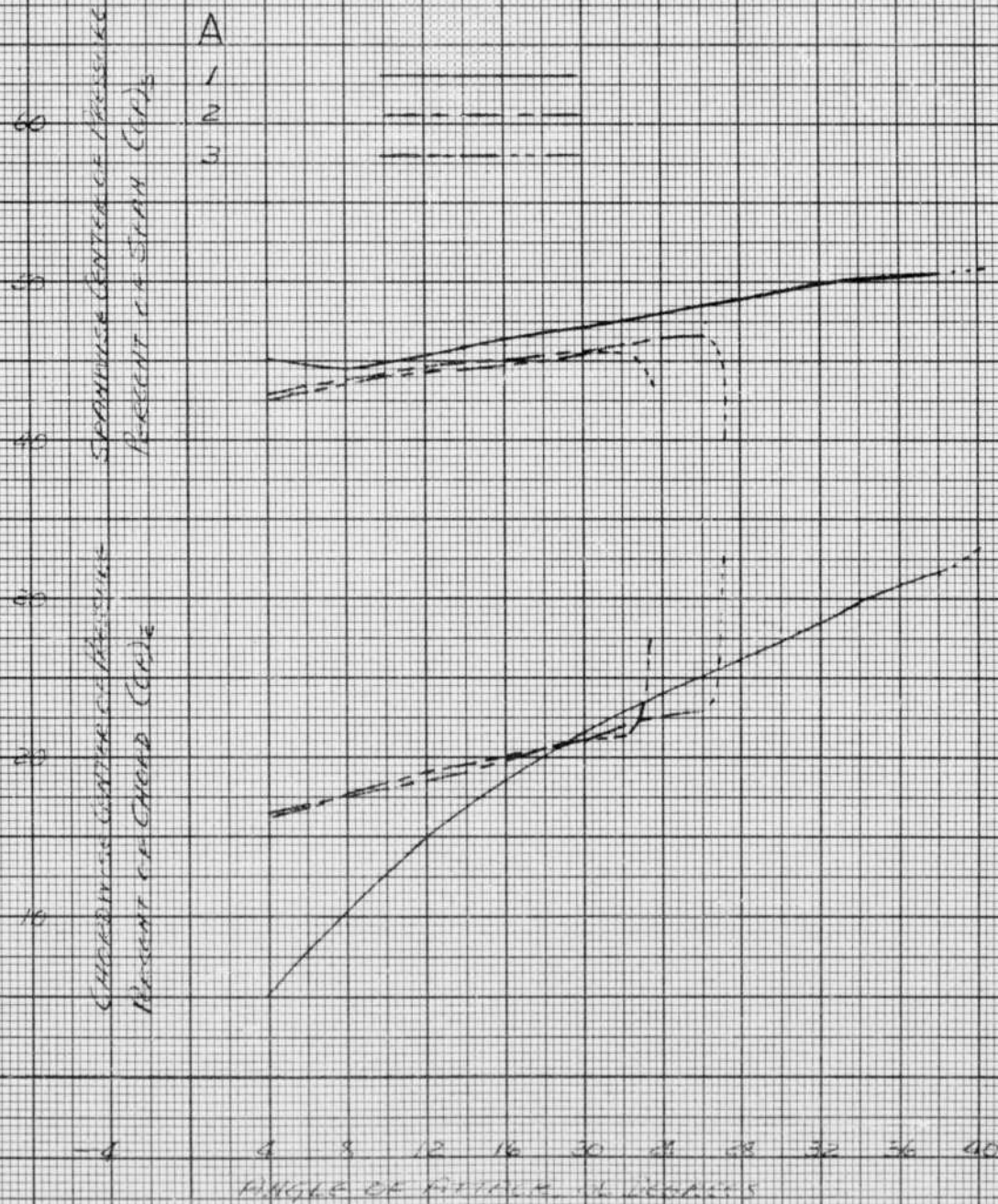


FIGURE 21

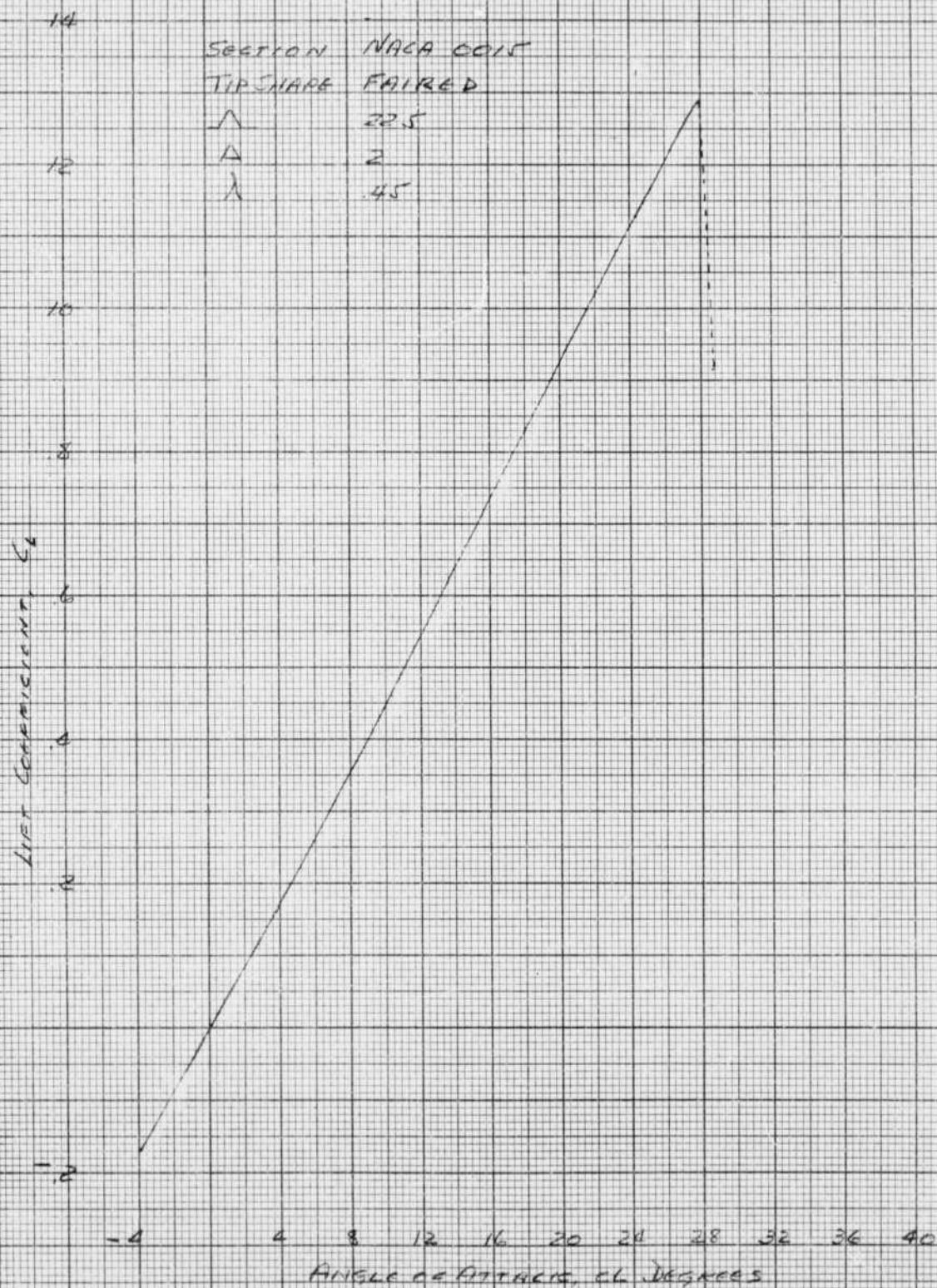


FIGURE 21A

SECTION NACA 6515
TIA SHAPE FAIRED
 Λ 22.5
A 2
 λ .45

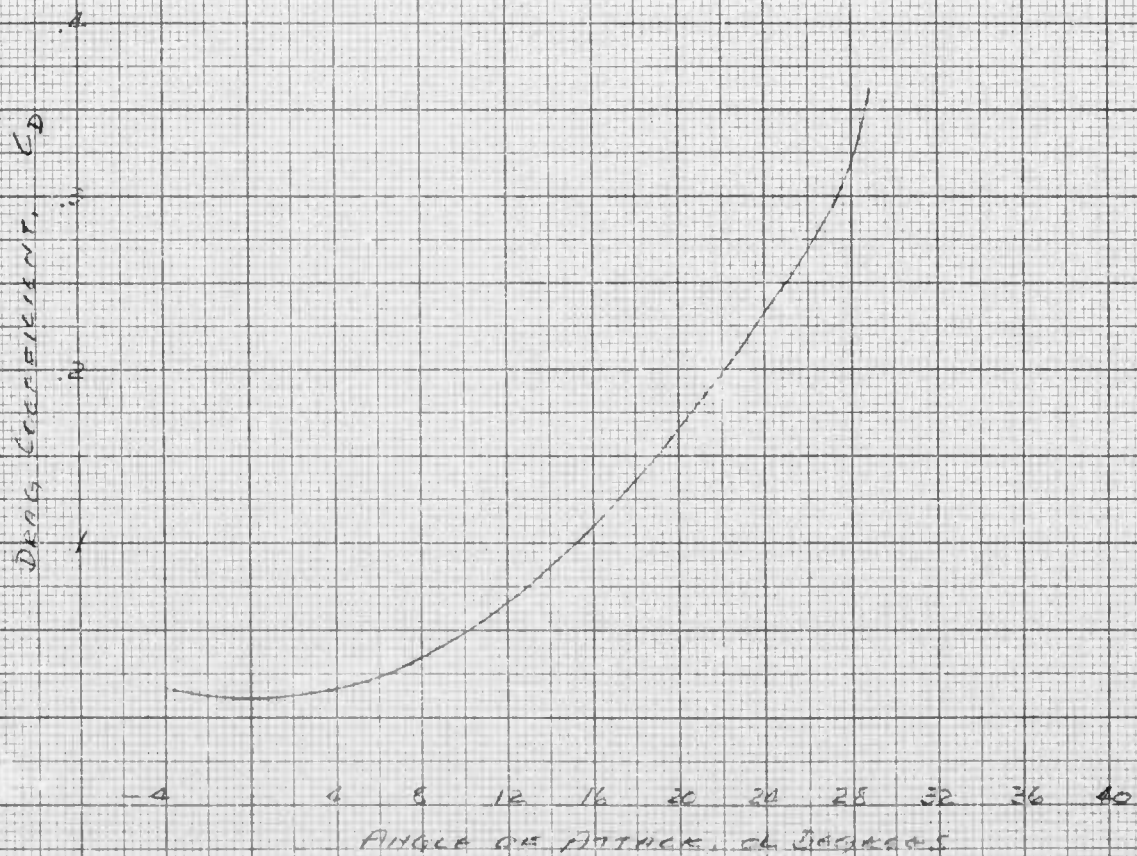


FIGURE 21 B

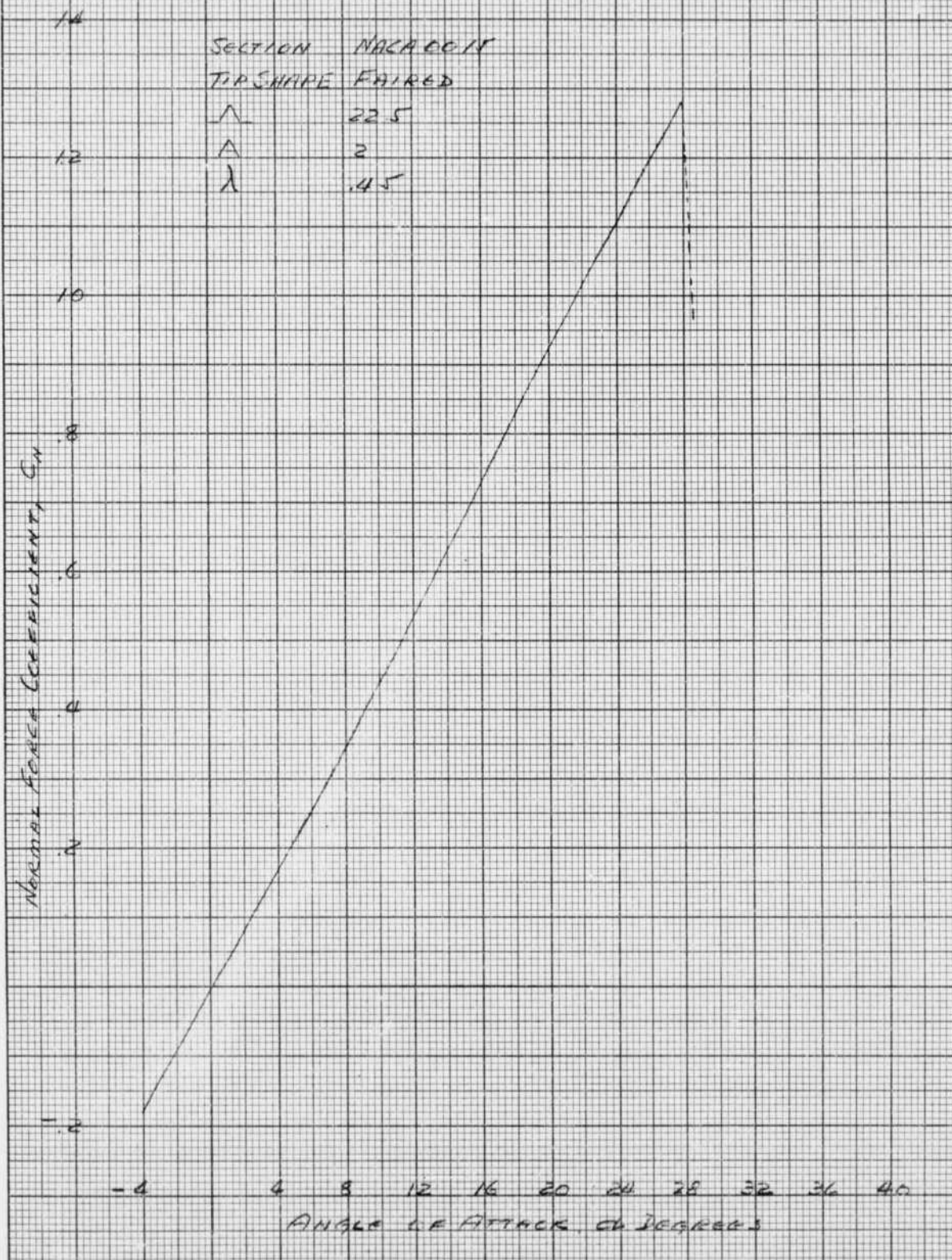


FIGURE 216

SECTION	NACA CELL
TIP SHAPE	FAIRED
Λ	22.5
Δ	2
λ	.45

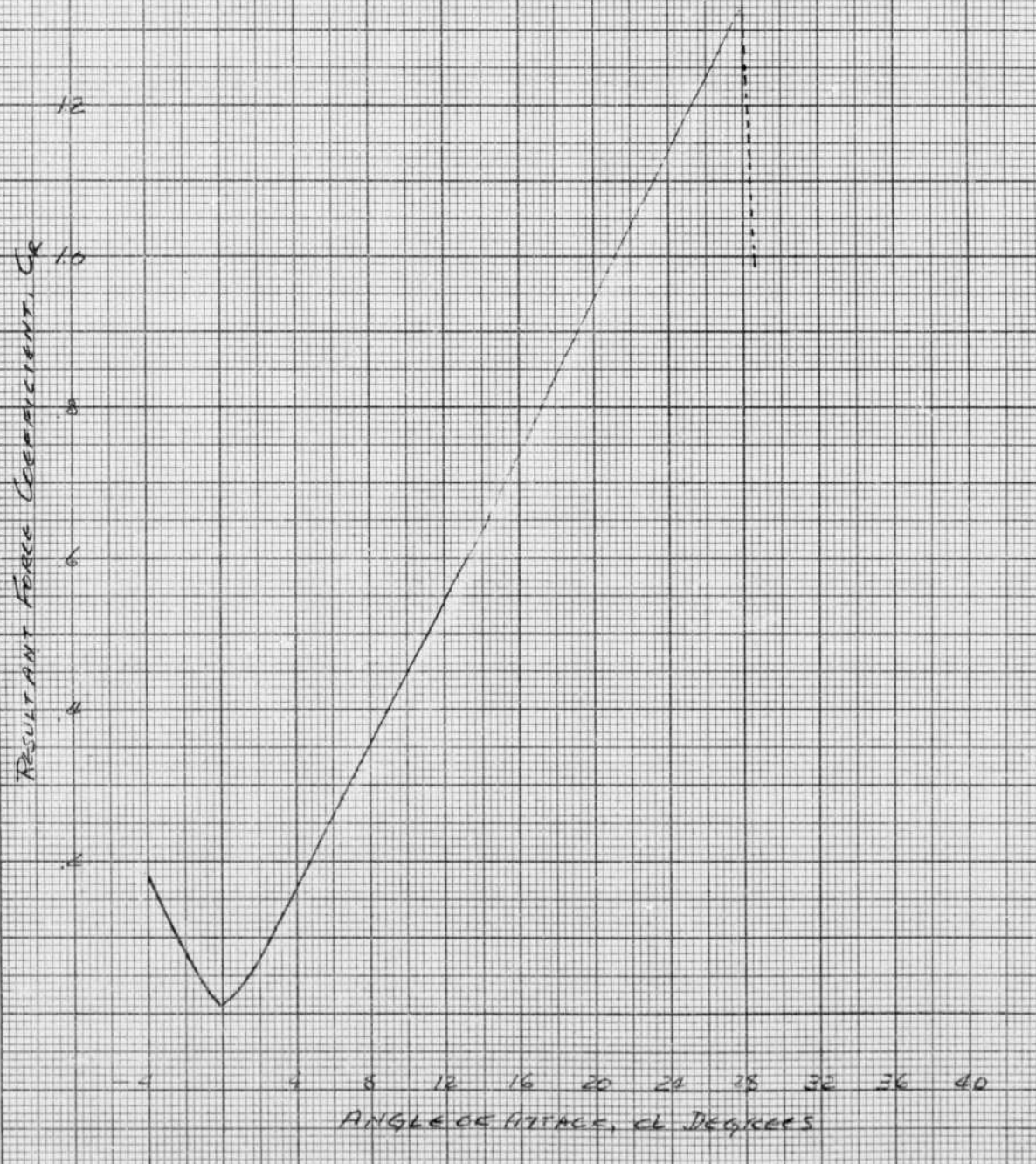


FIGURE 21D

SECTION	NACA 0015
TRAILING EDGE	FAIRED
α	22.5
λ	2
λ	.45

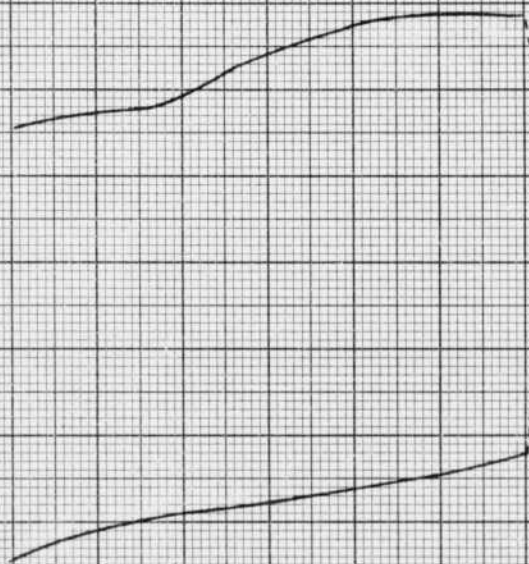
SPINNER CENTER OF PRESSURE
PERCENT OF SPAN, (CP)₅

CHORDWISE CENTER OF PRESSURE
PERCENT OF CHORD, (CP)₂

10

4 8 12 16 20 24 28 32 36 40

ANGLE OF ATTACK, α , DEGREES



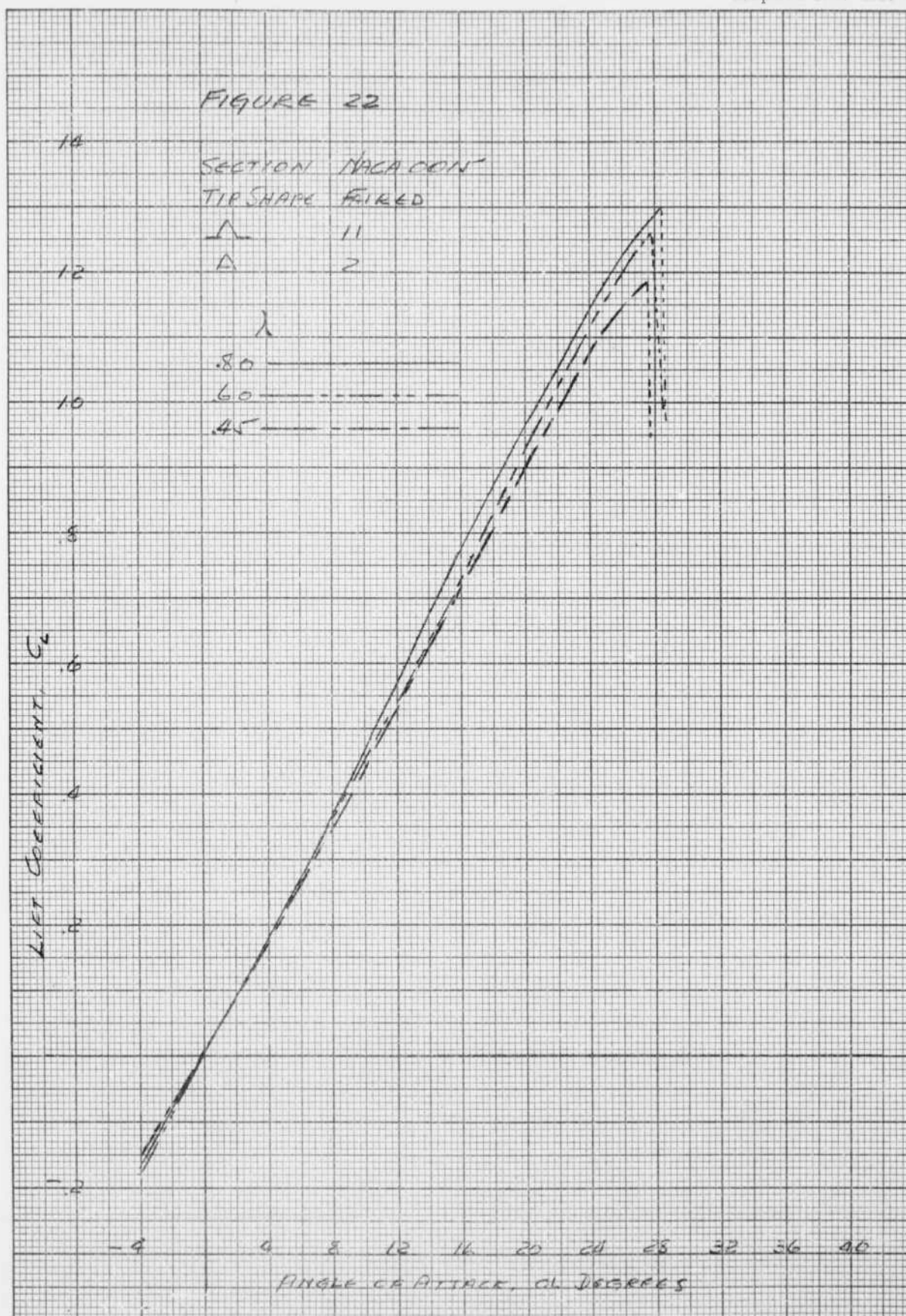


FIGURE 22A

SECTION NACA 0011

TIP SHAPE FAIRED

Λ 11

A 2

λ

.80 —————

.60 - - - - -

.45 - - - - -

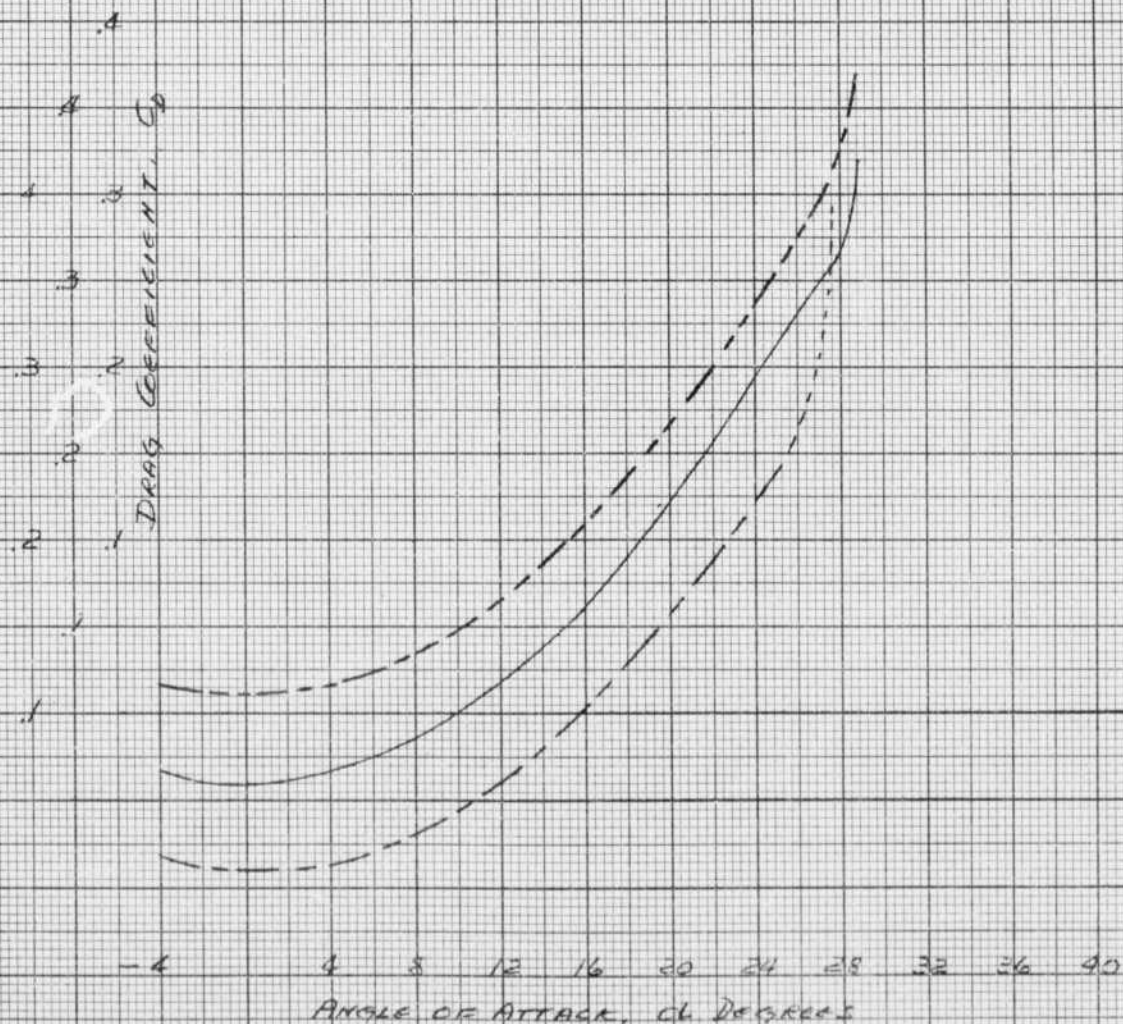


FIGURE 22 B

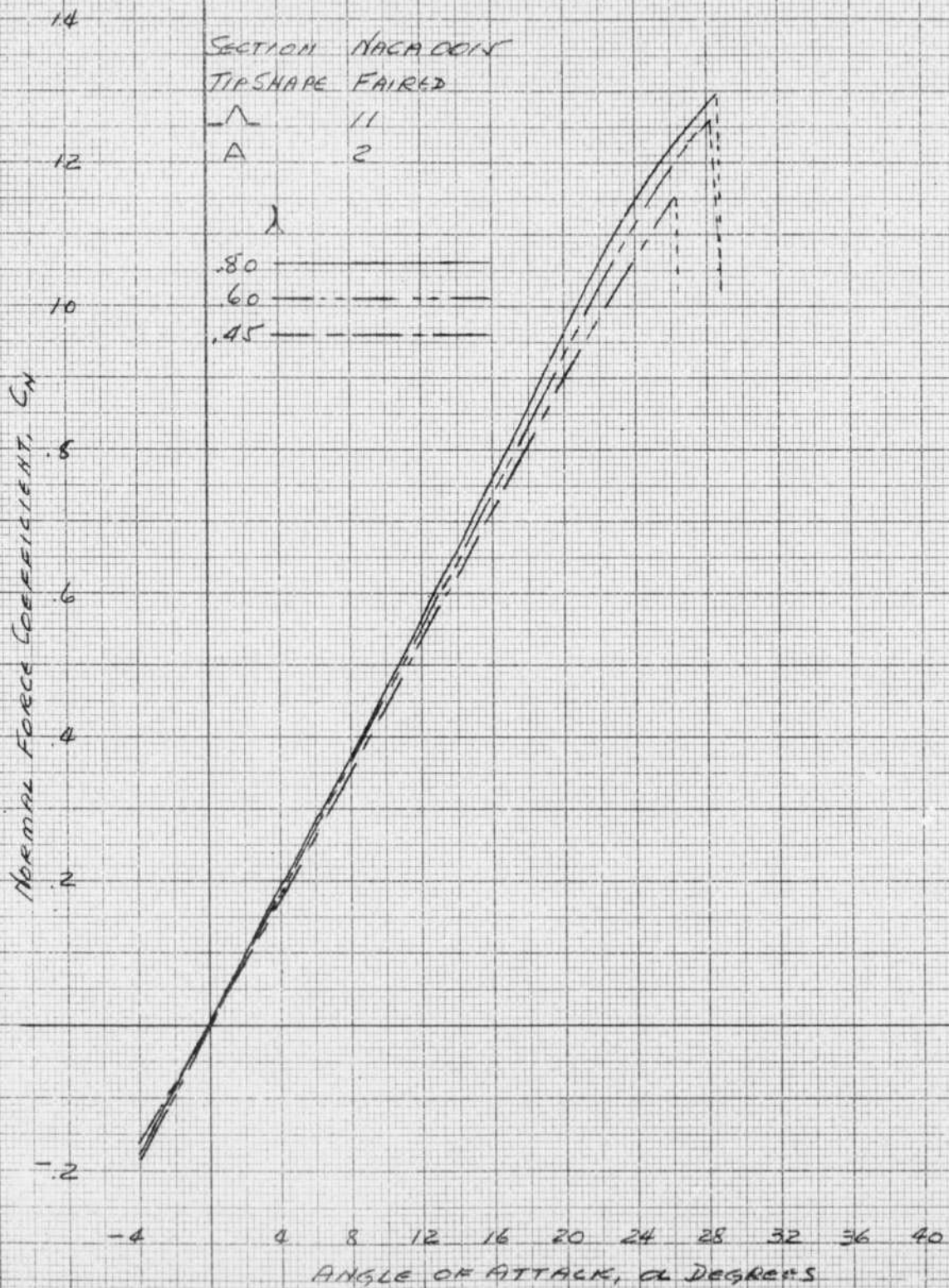


FIGURE 22 C

SECTION NACA 0015

TIP SHAPE FAIRED

Δ 11

Δ 2

λ

.80

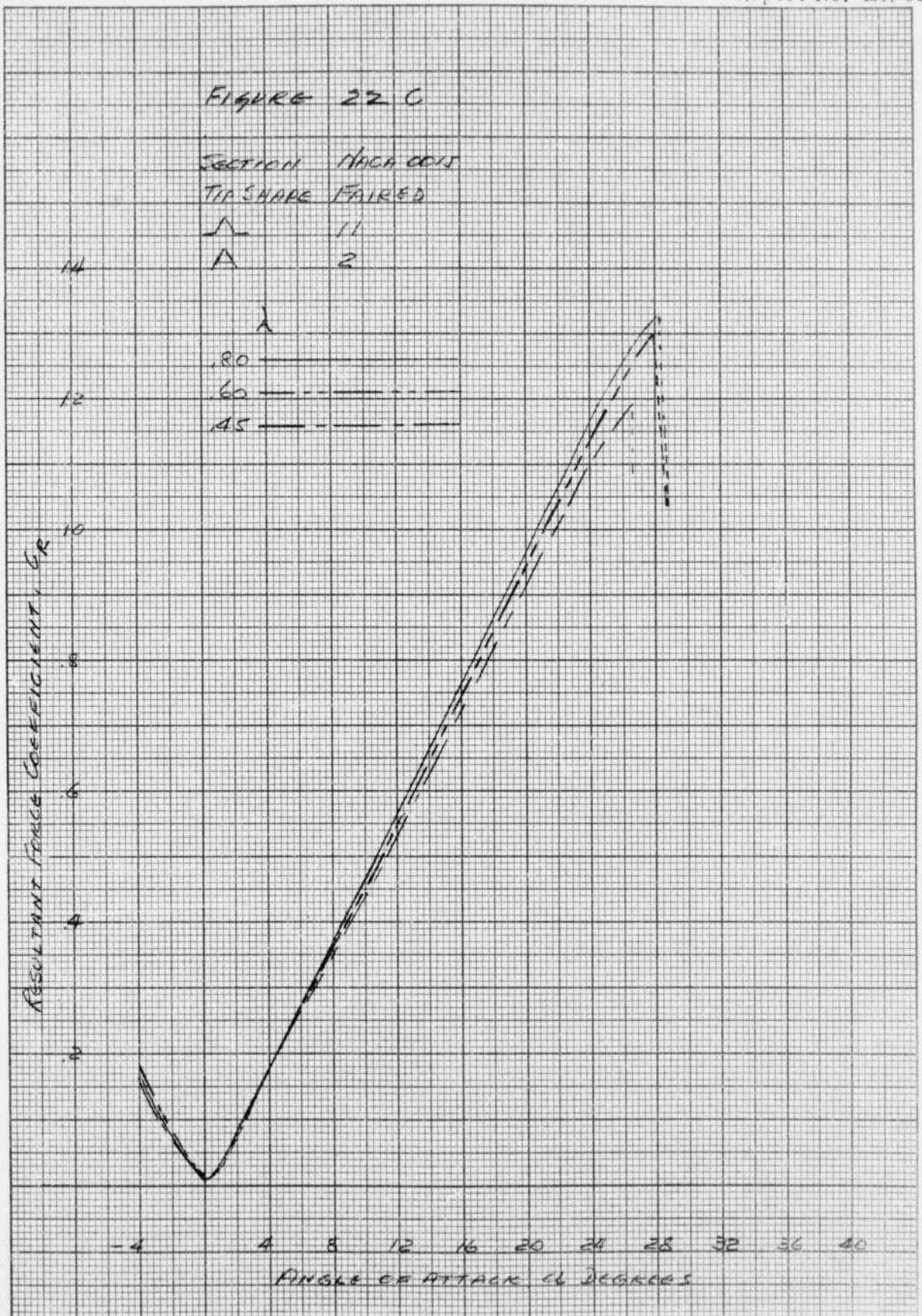
.60

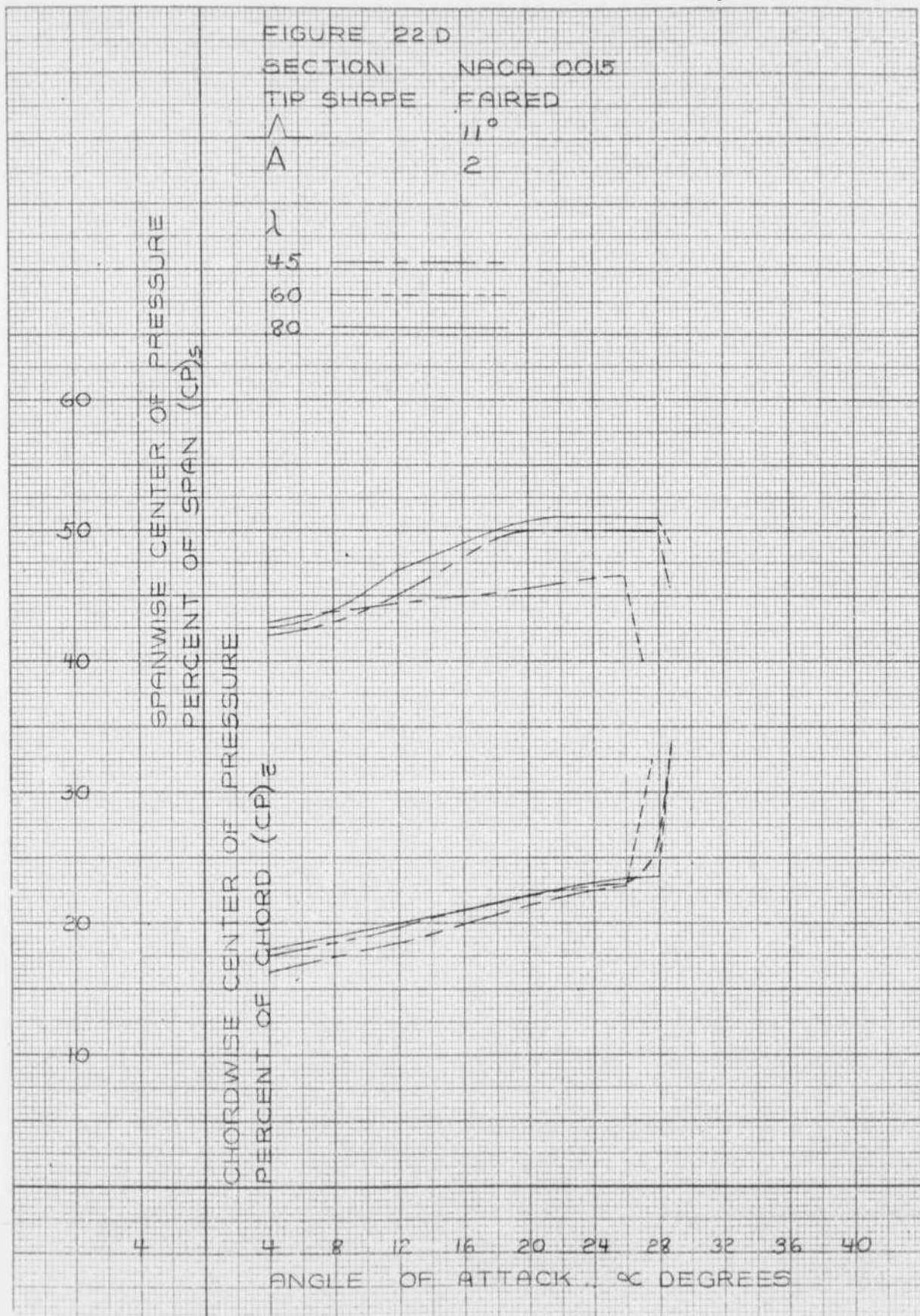
.45

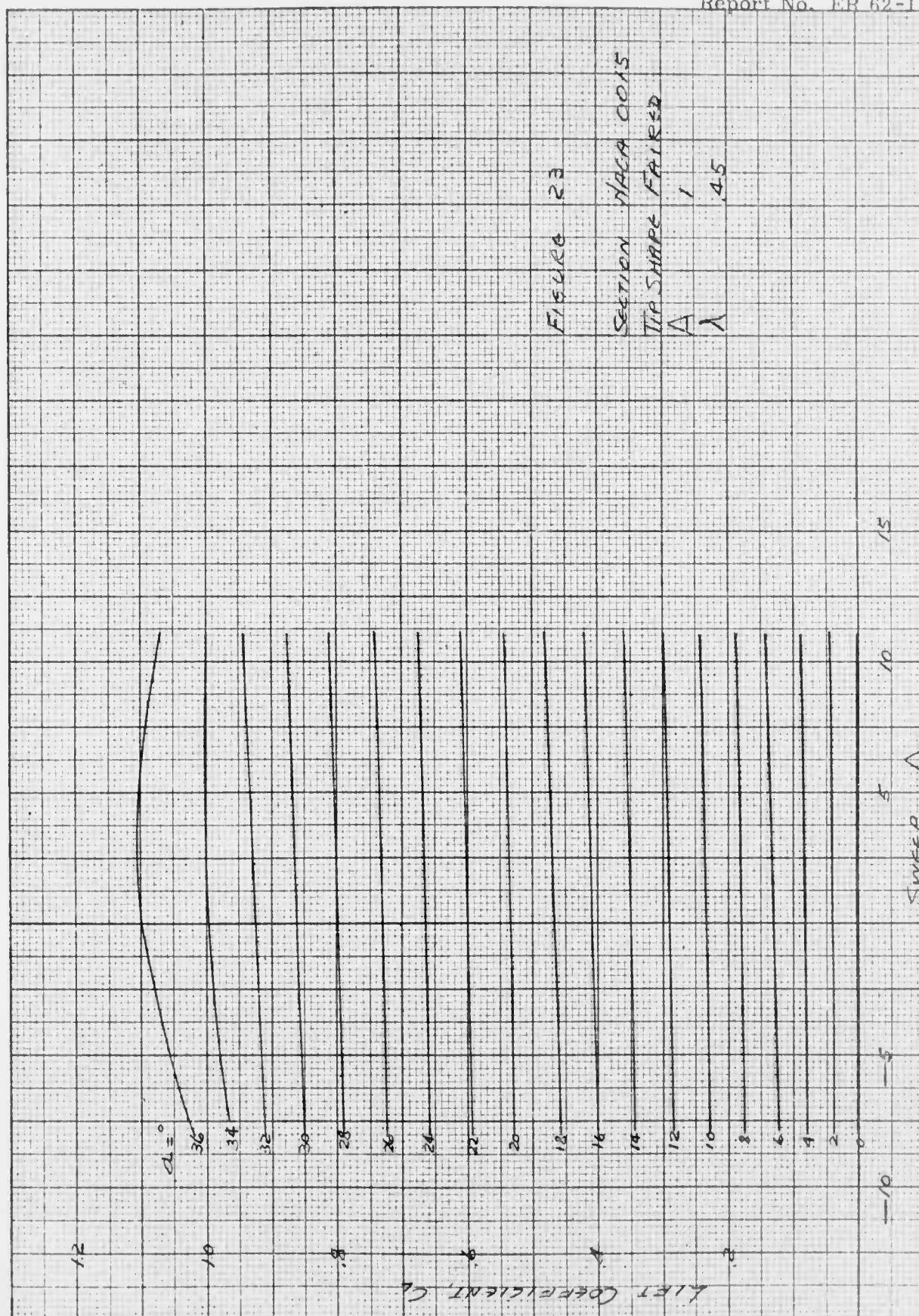
RESULTANT FORCE COEFFICIENT, C_R

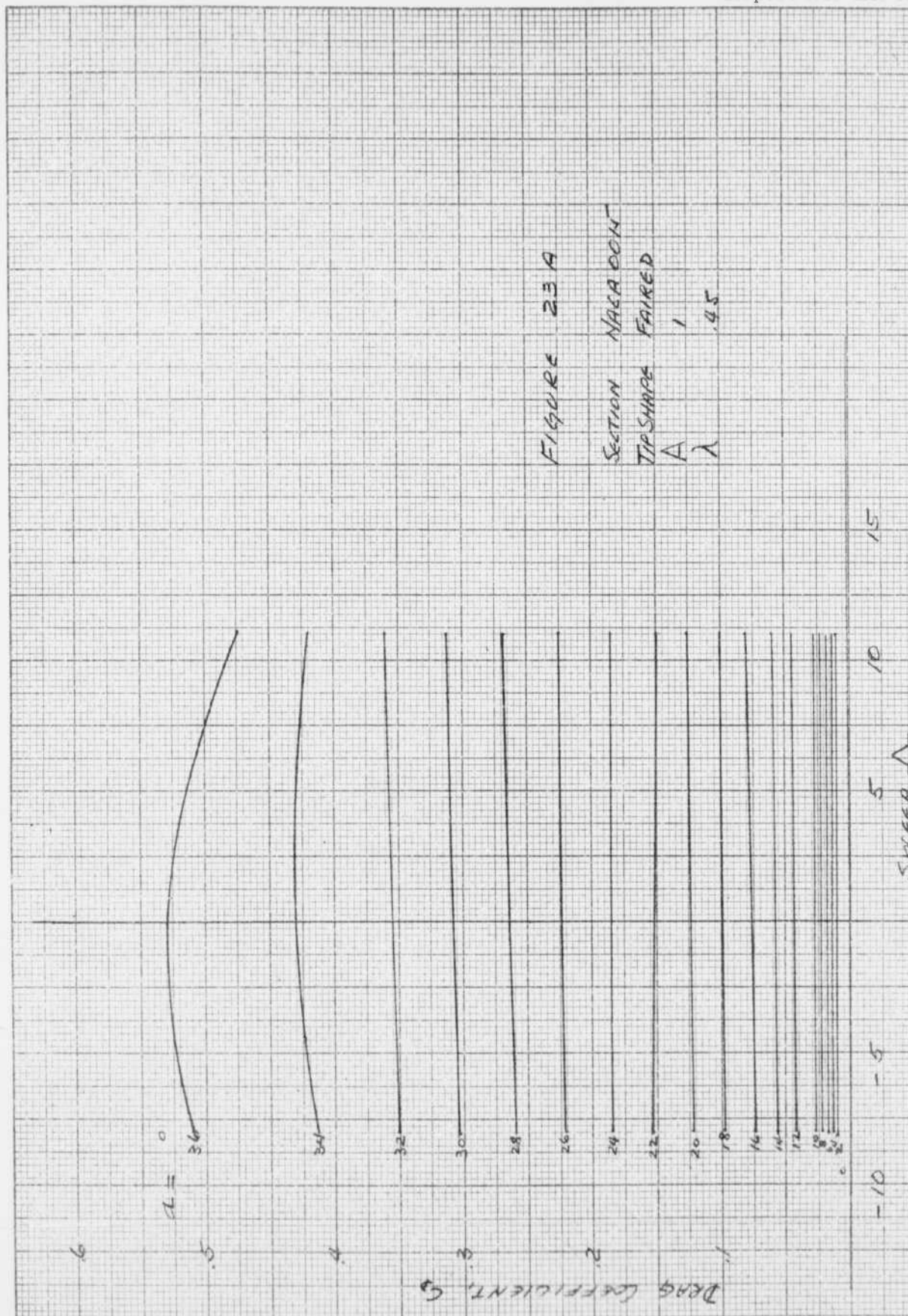
-4 4 8 12 16 20 24 28 32 36 40

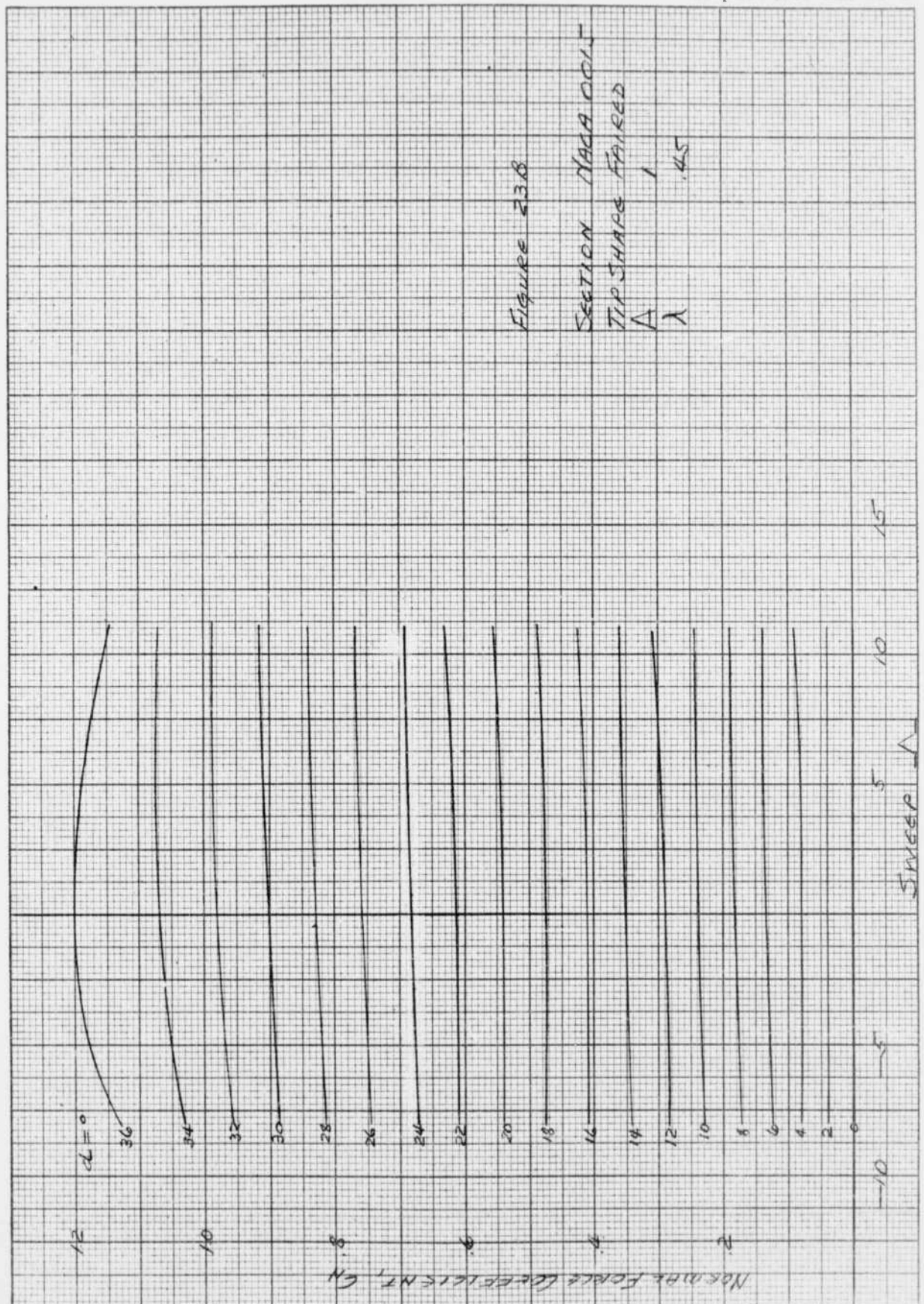
ANGLE OF ATTACK α DEGREES

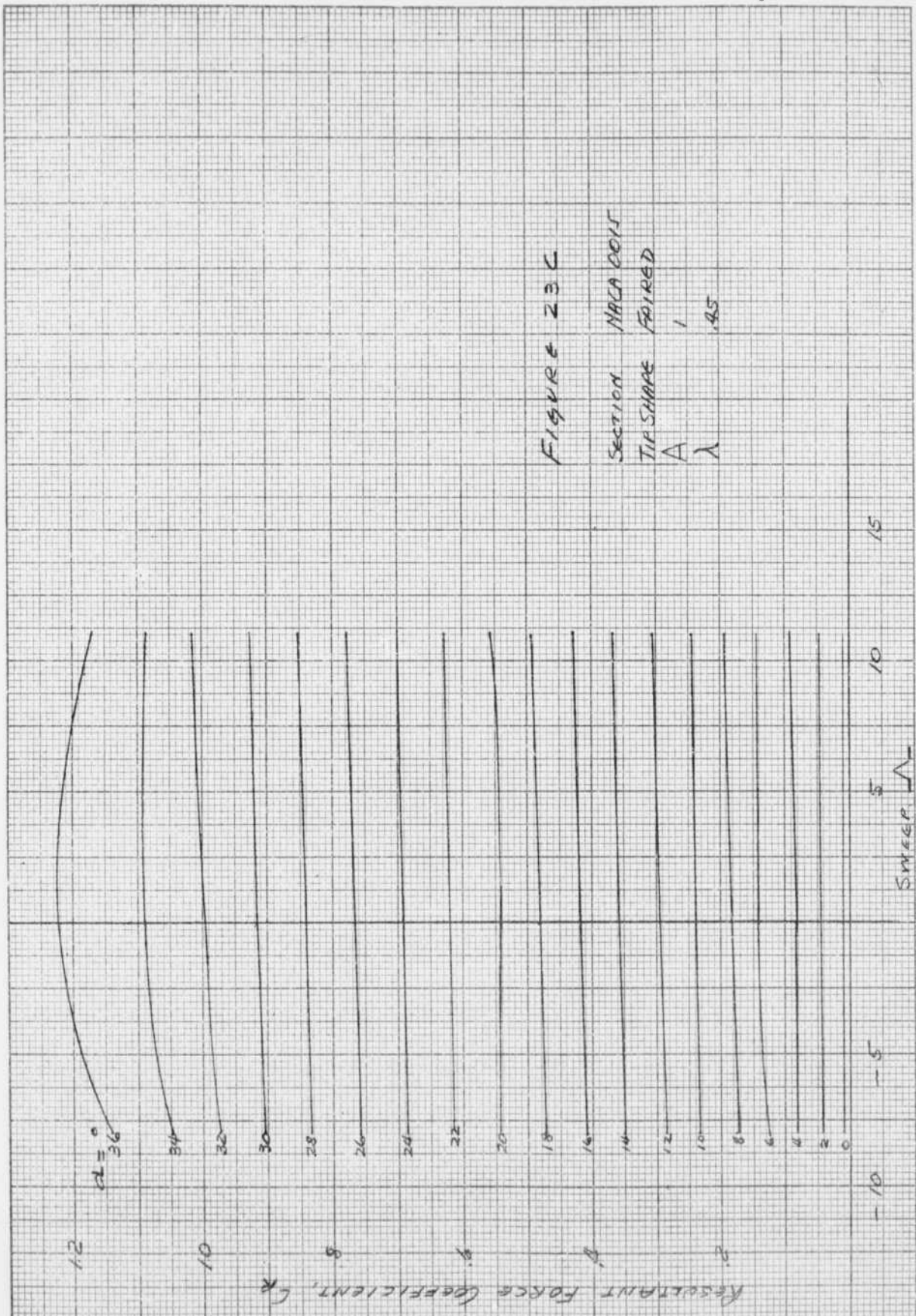


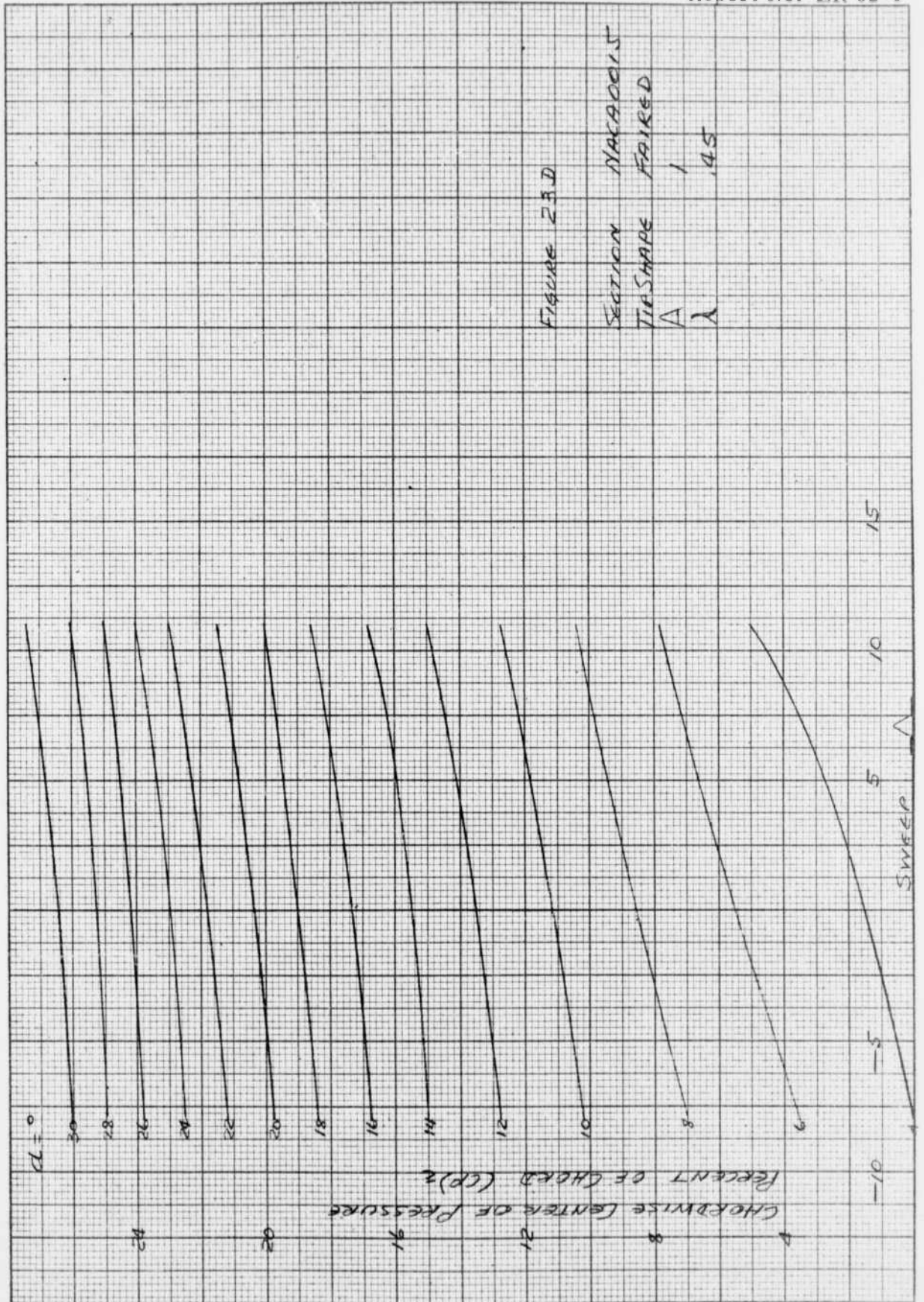


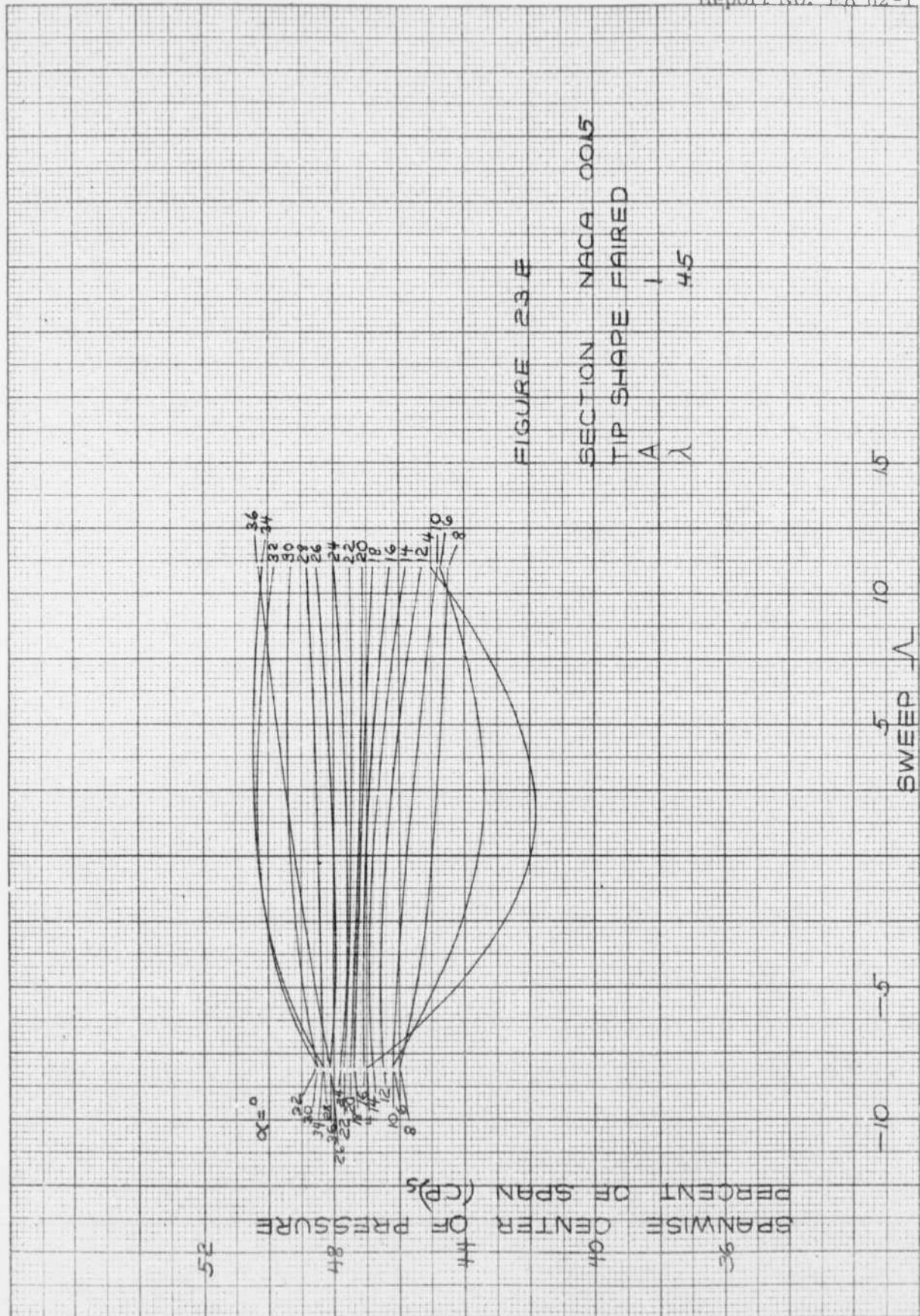


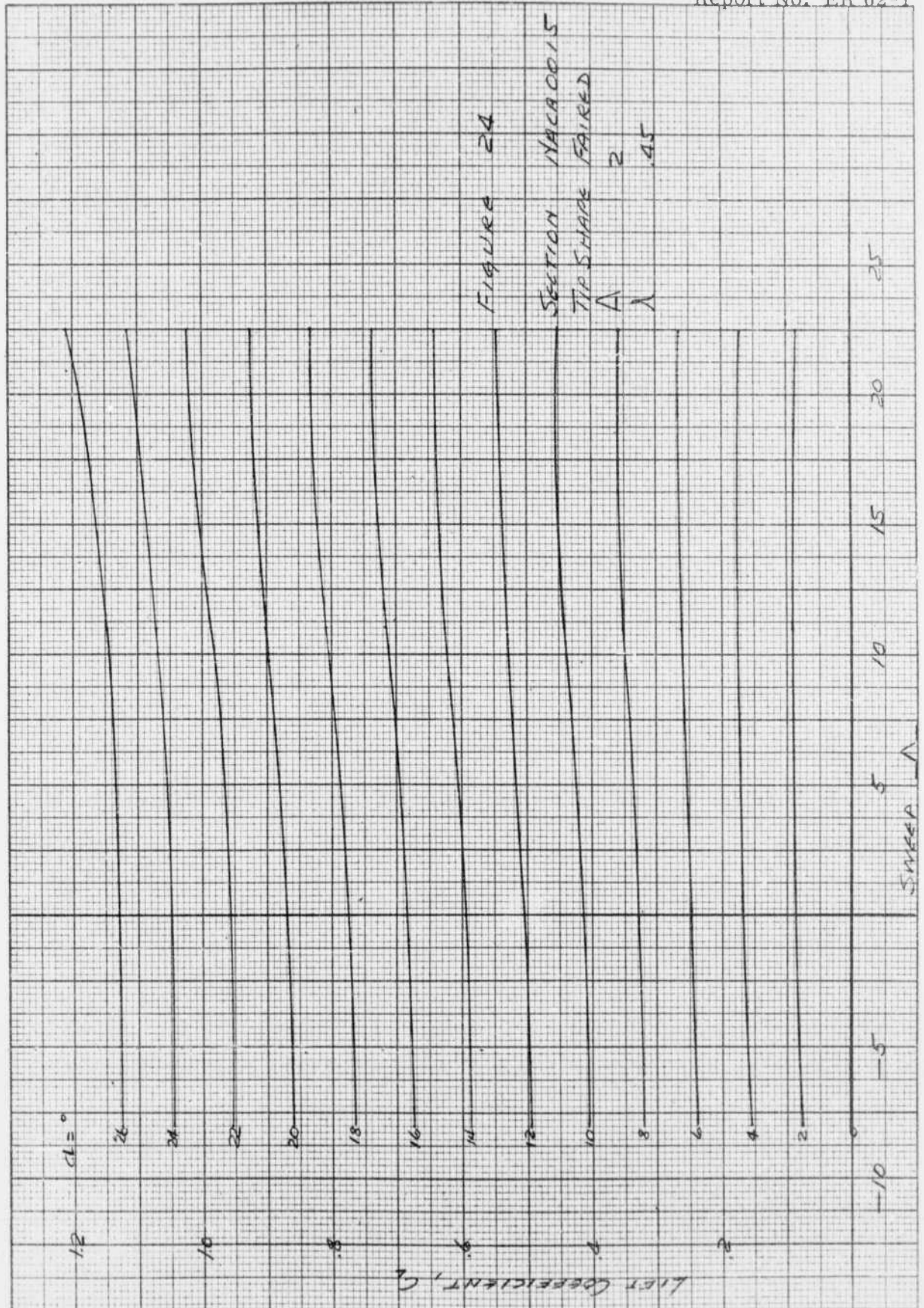


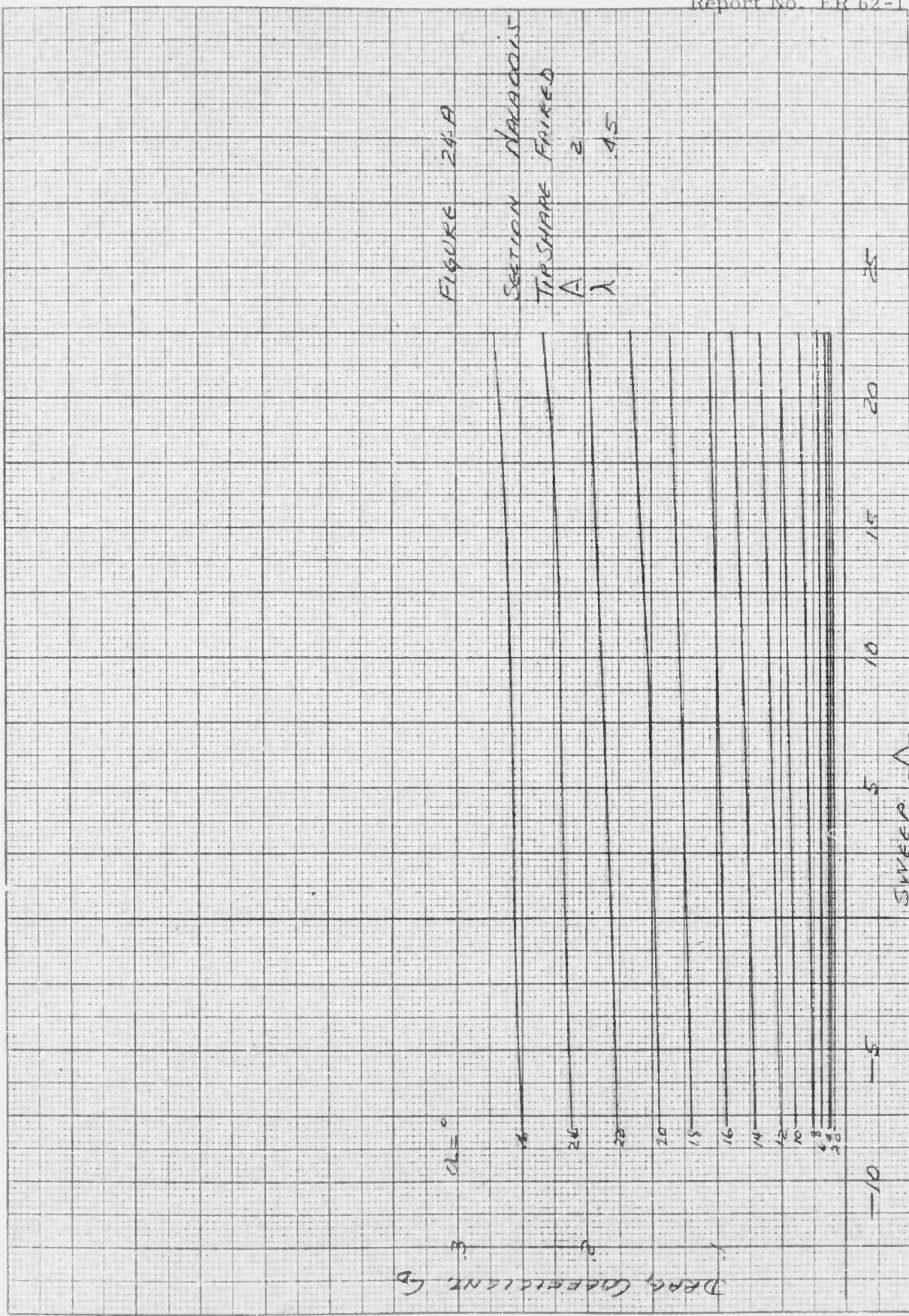


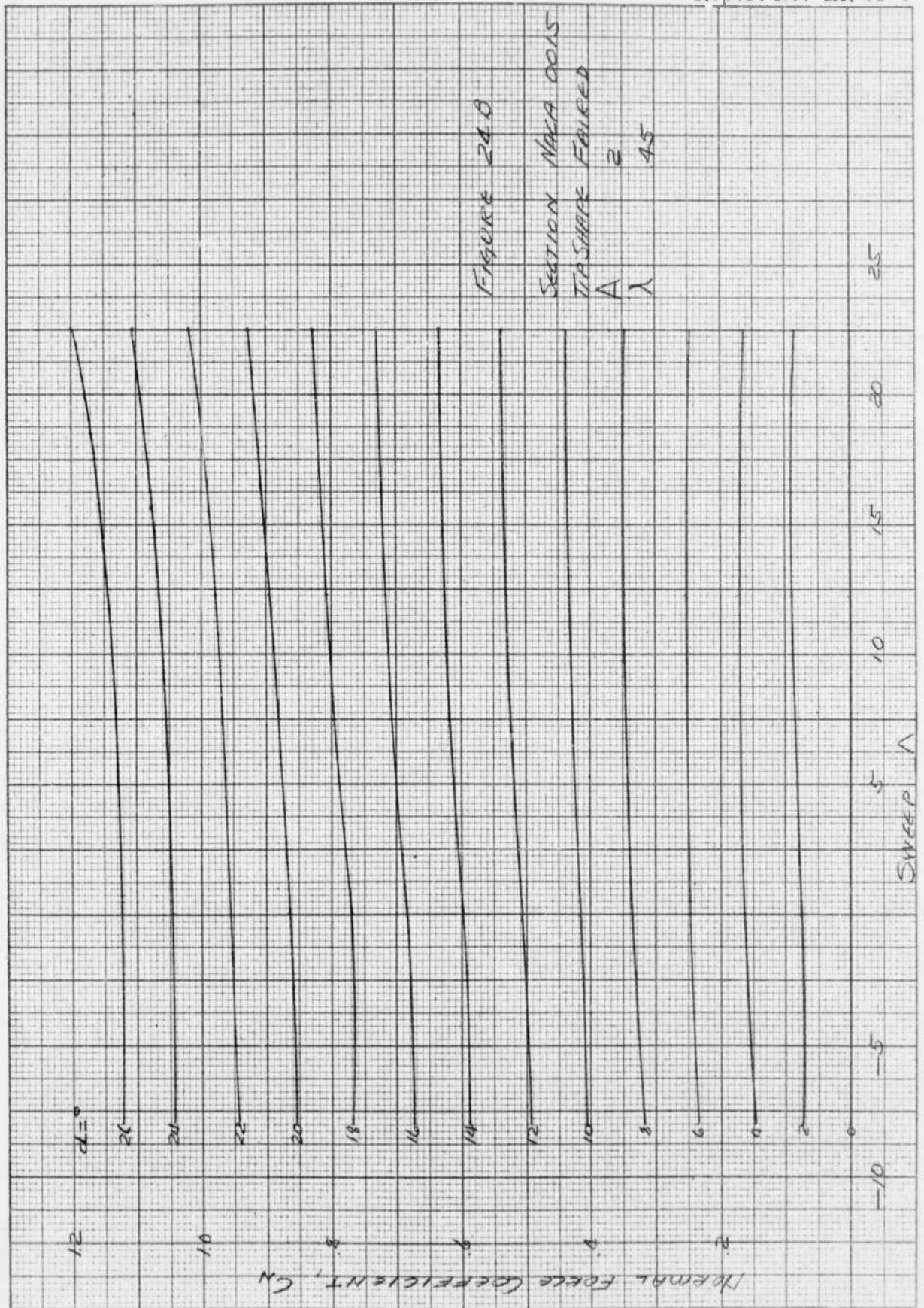


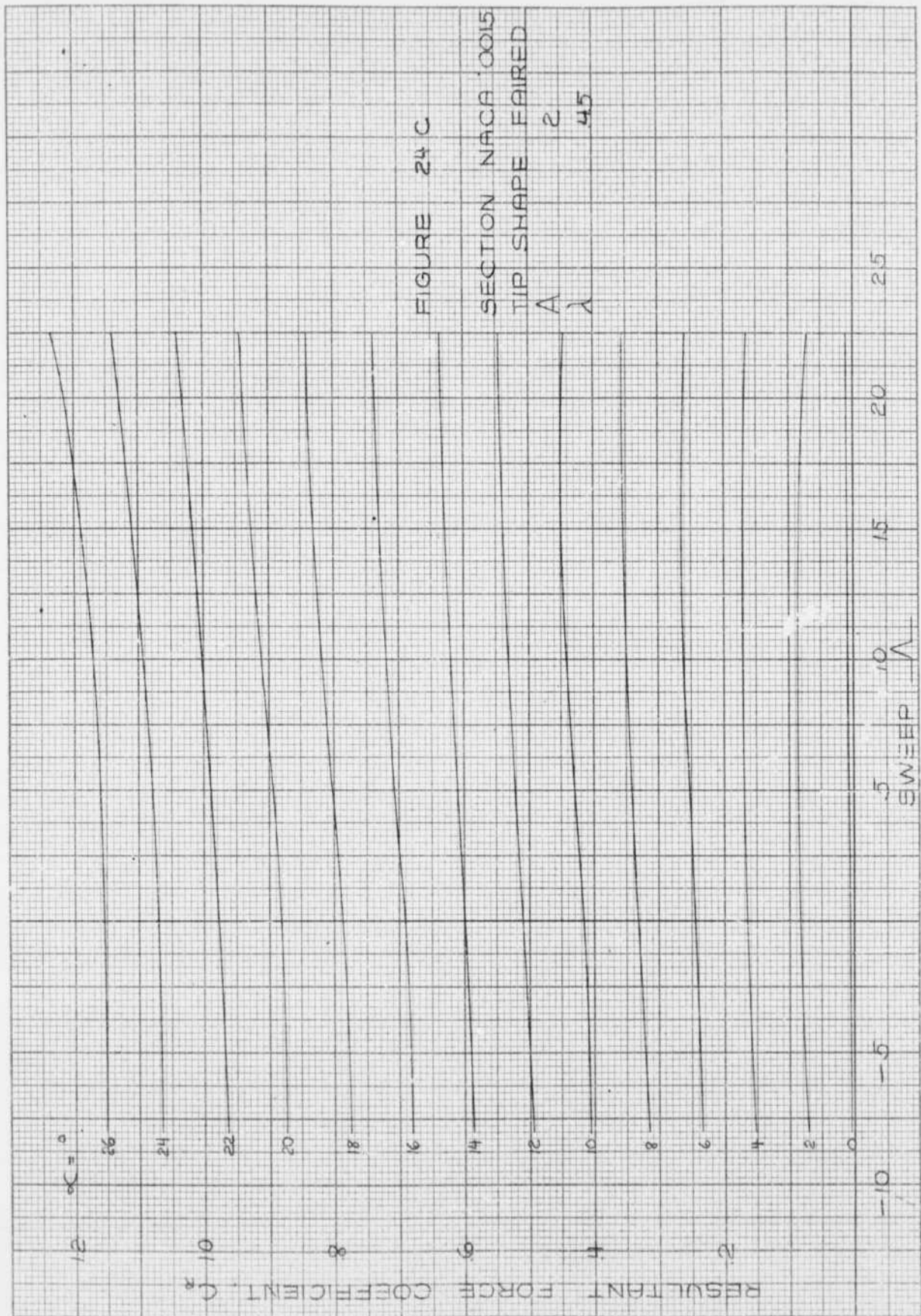


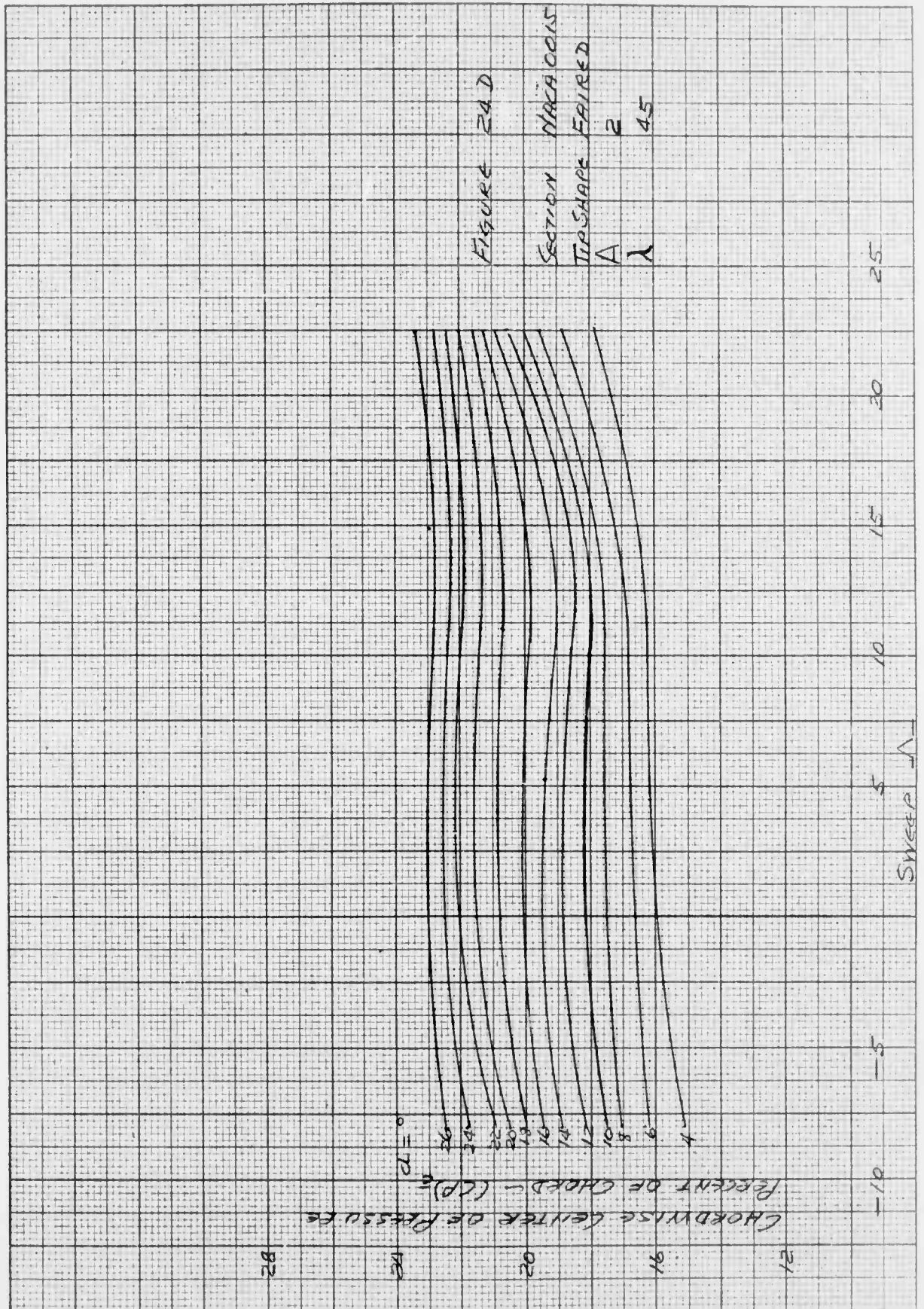


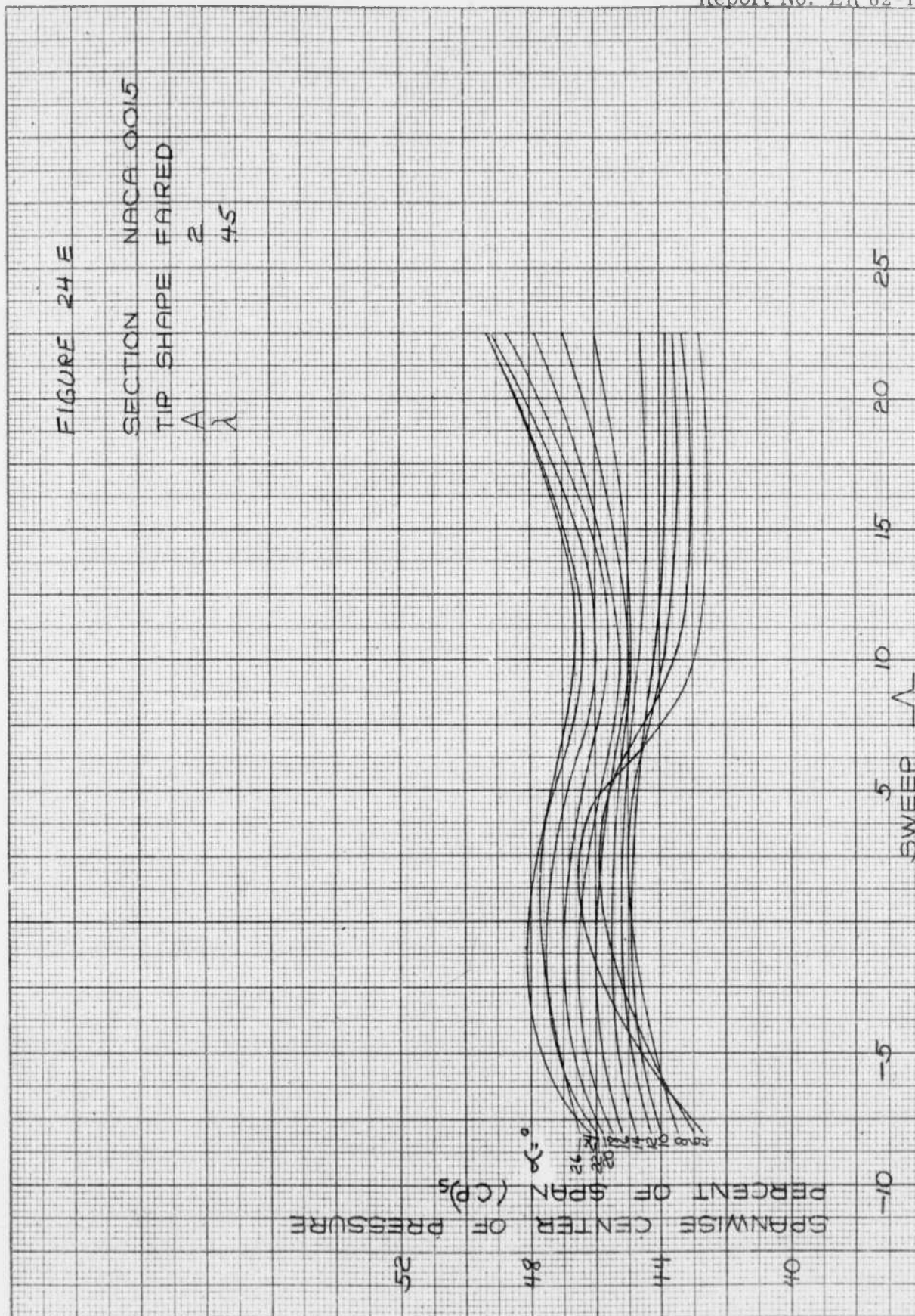


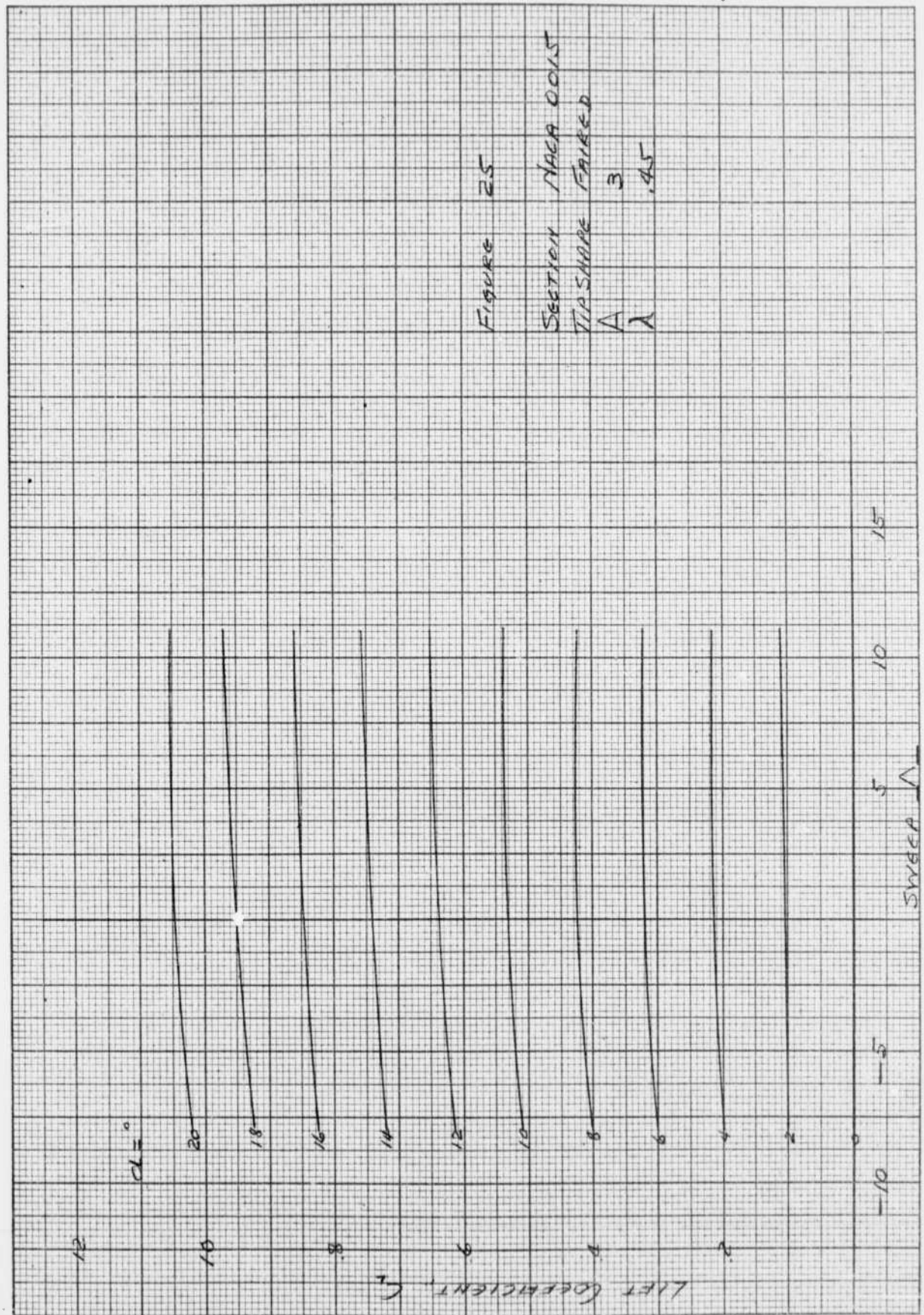


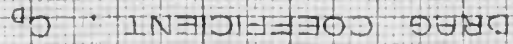


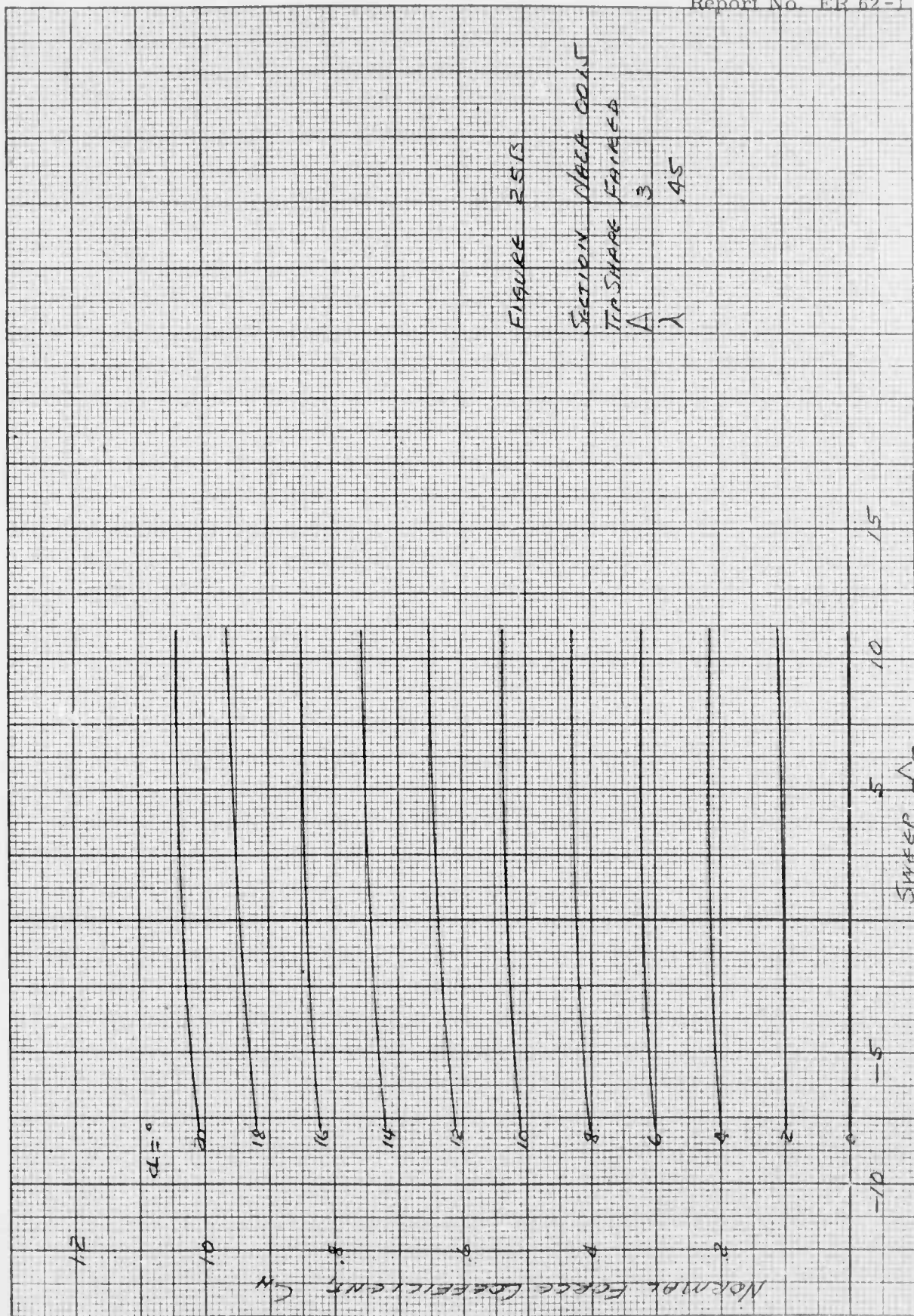


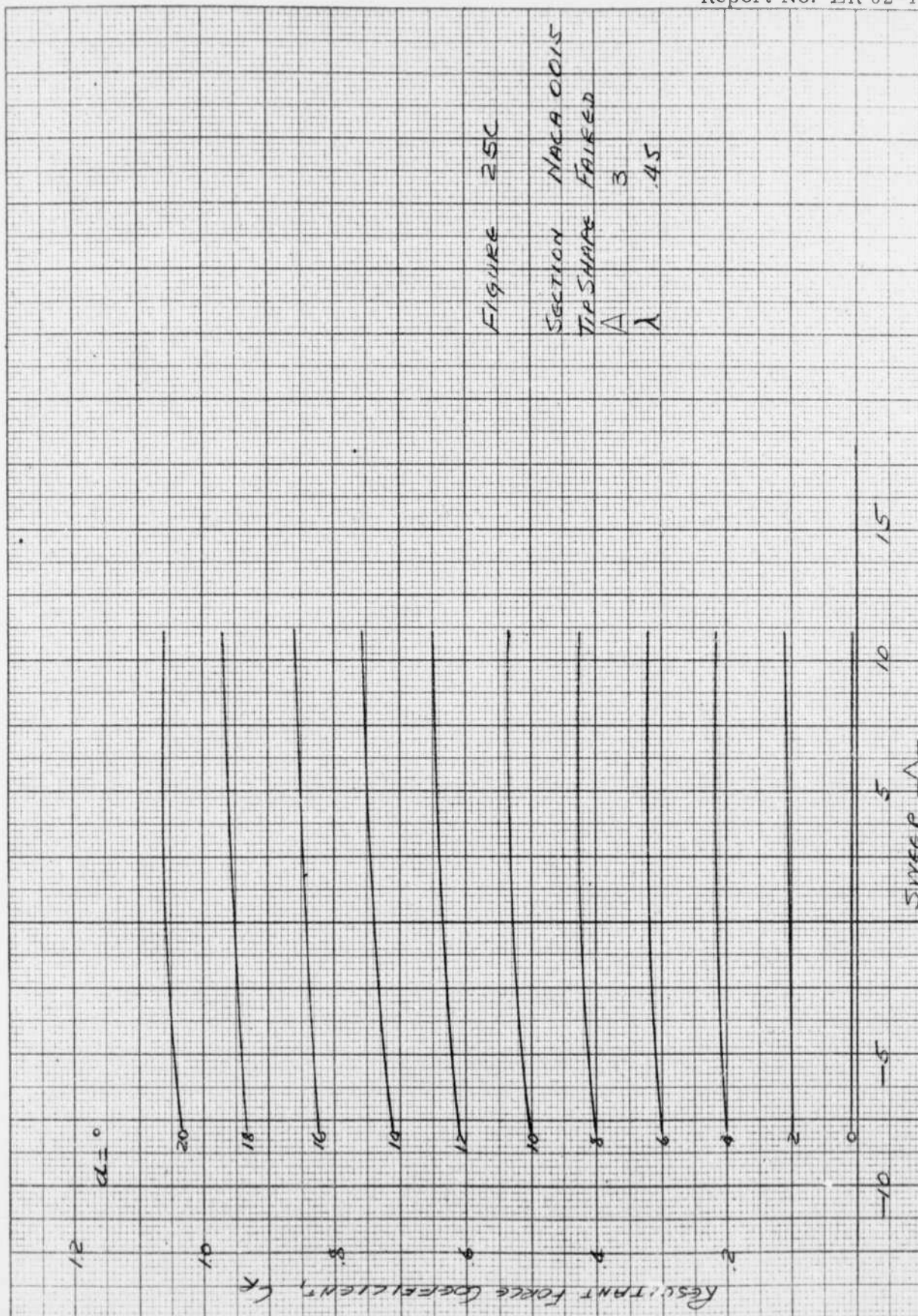


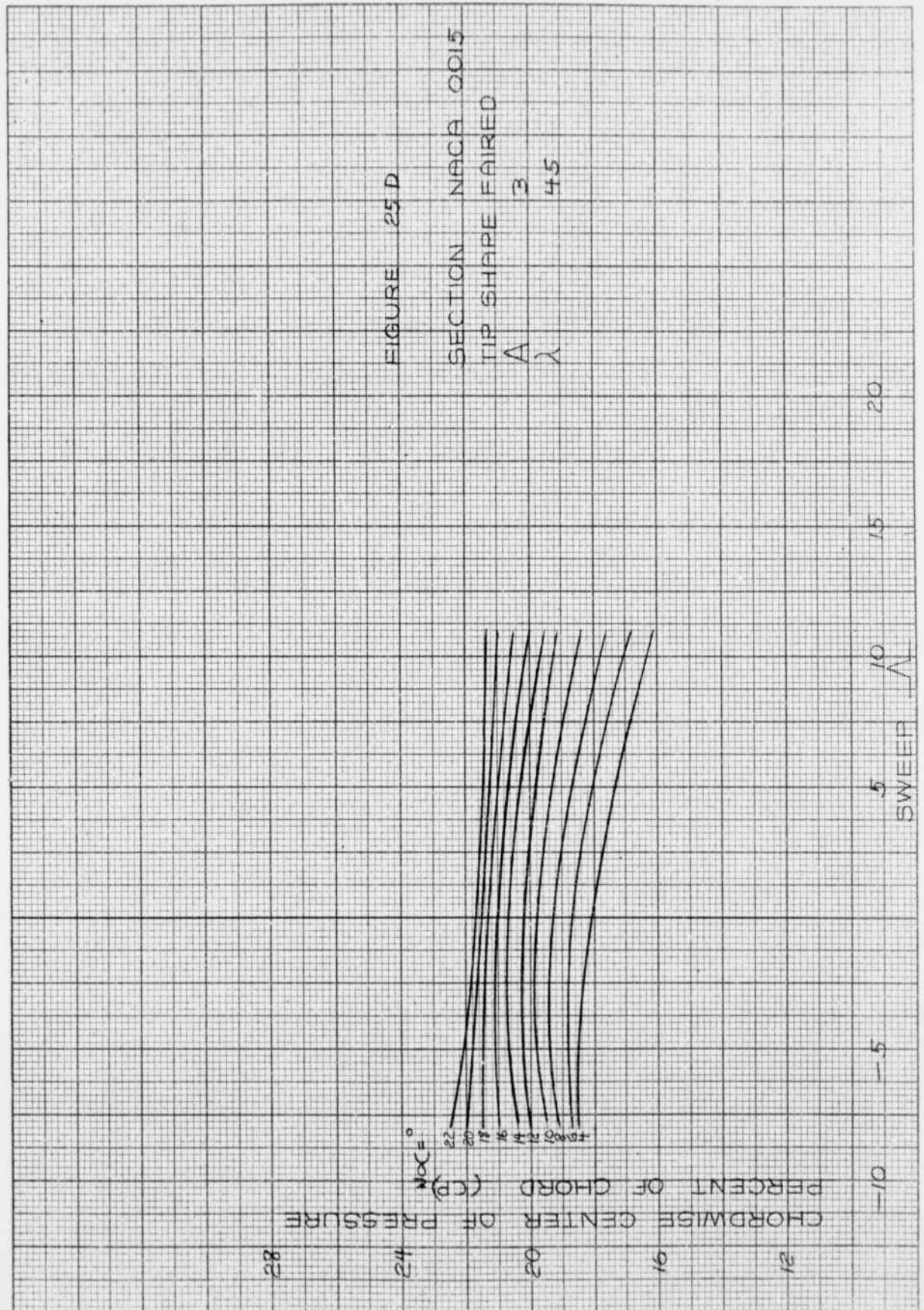


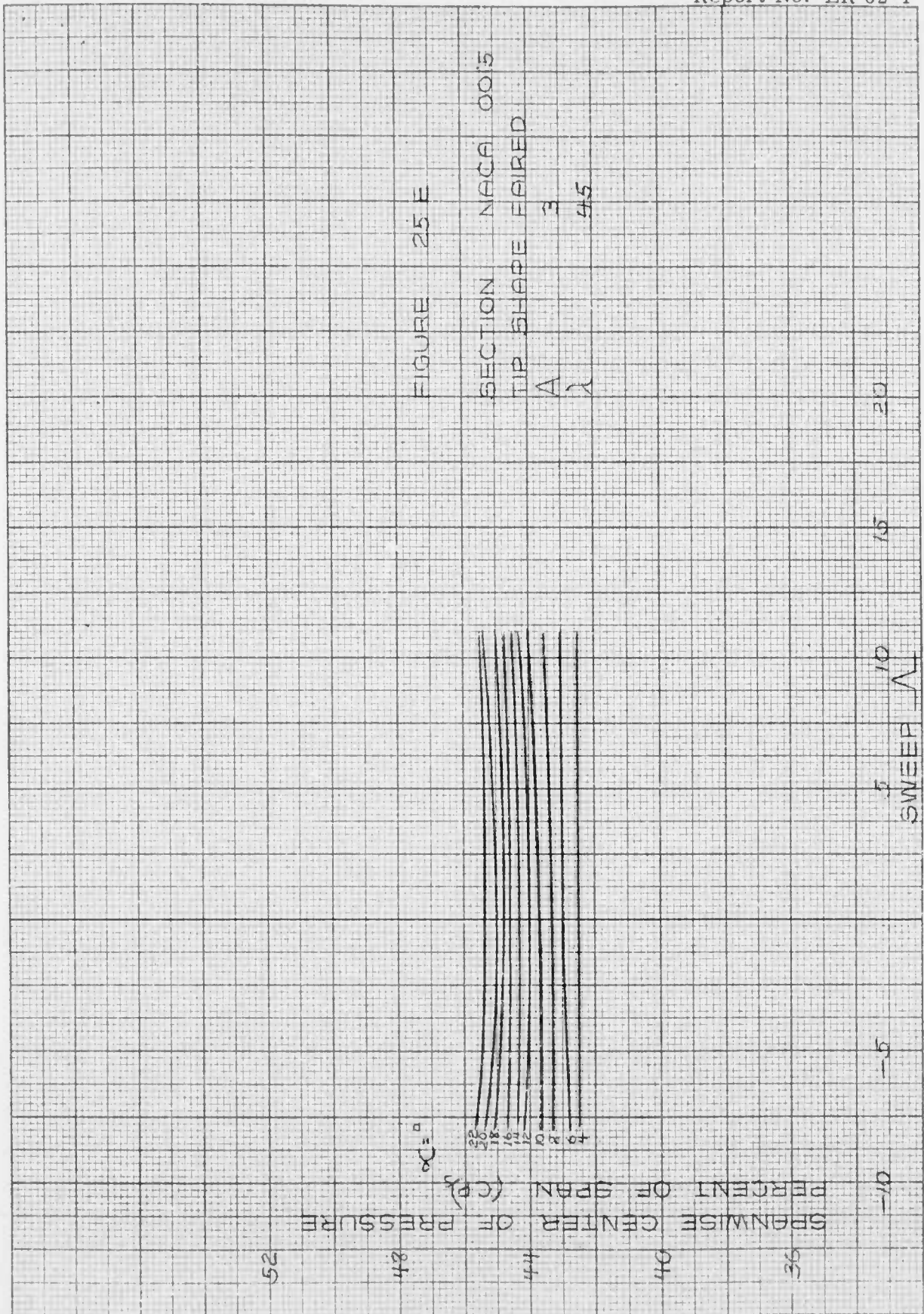


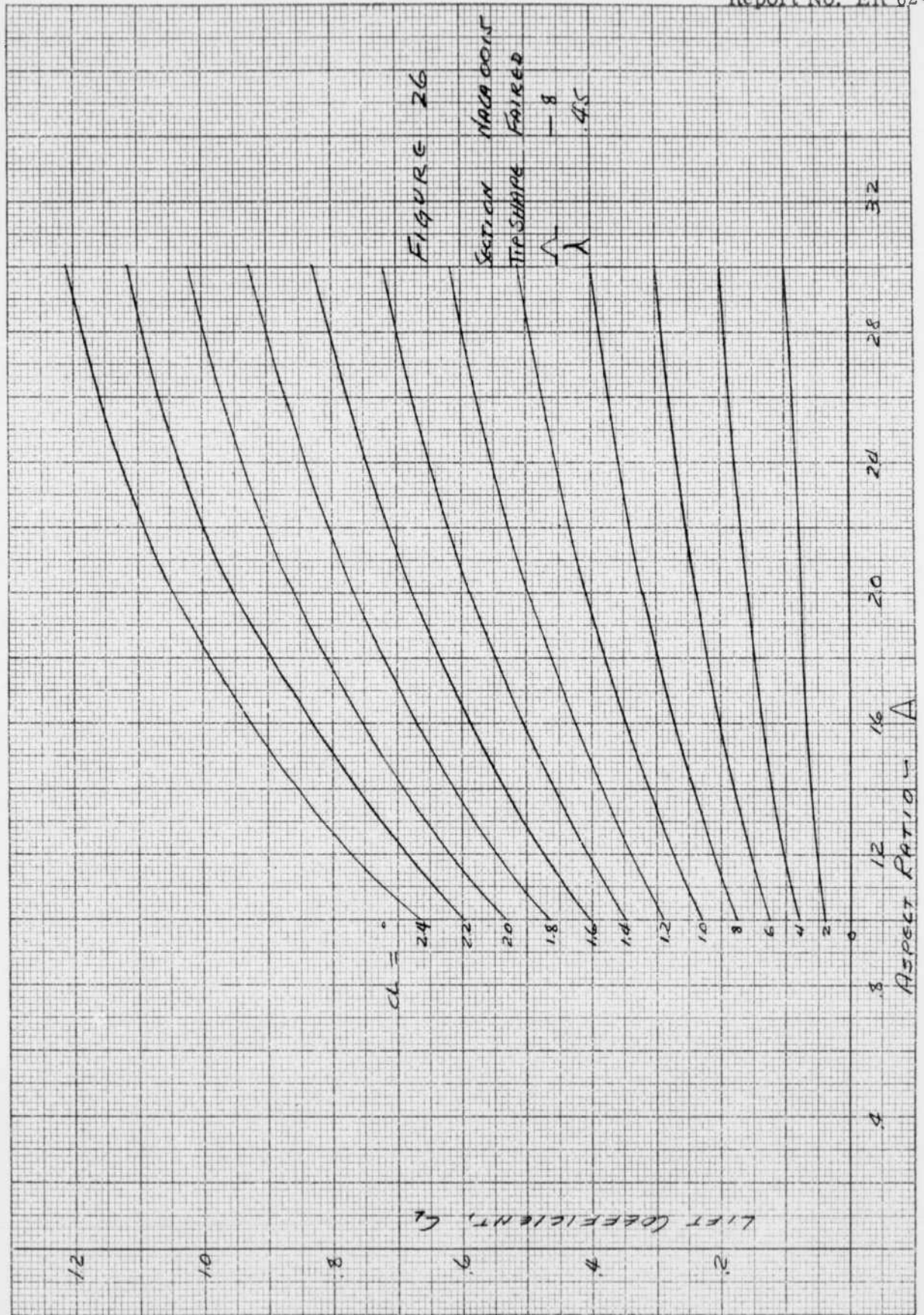


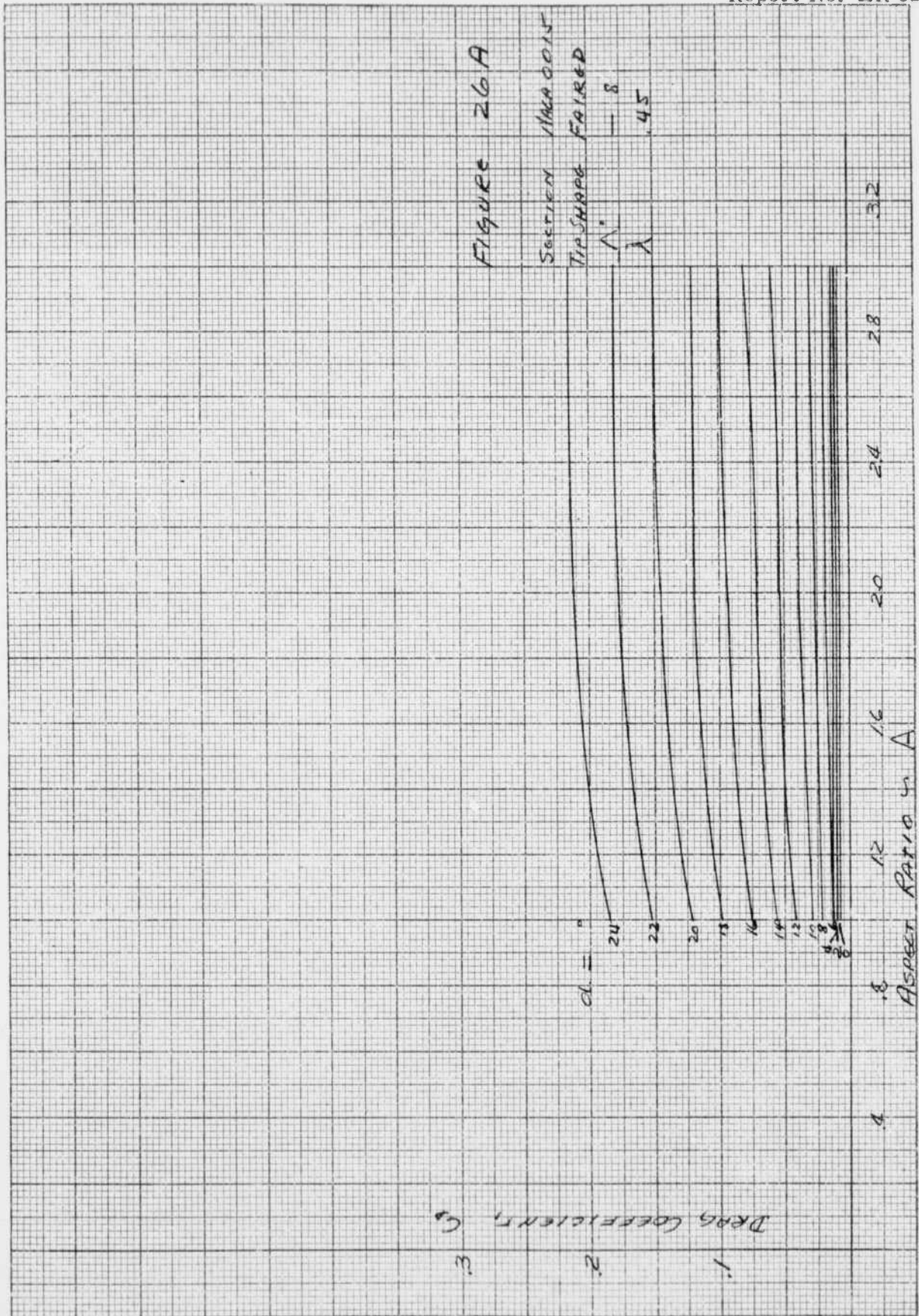


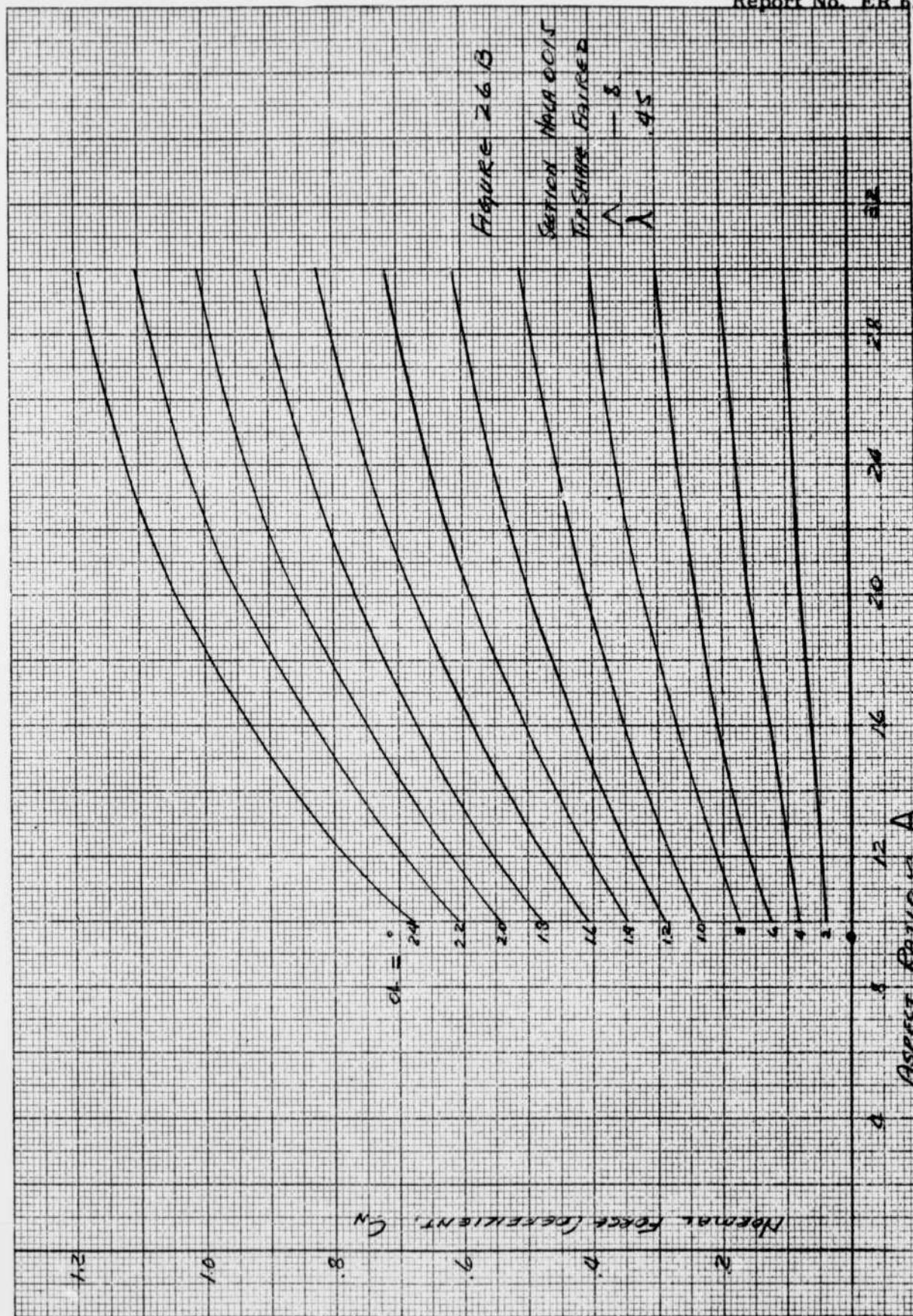


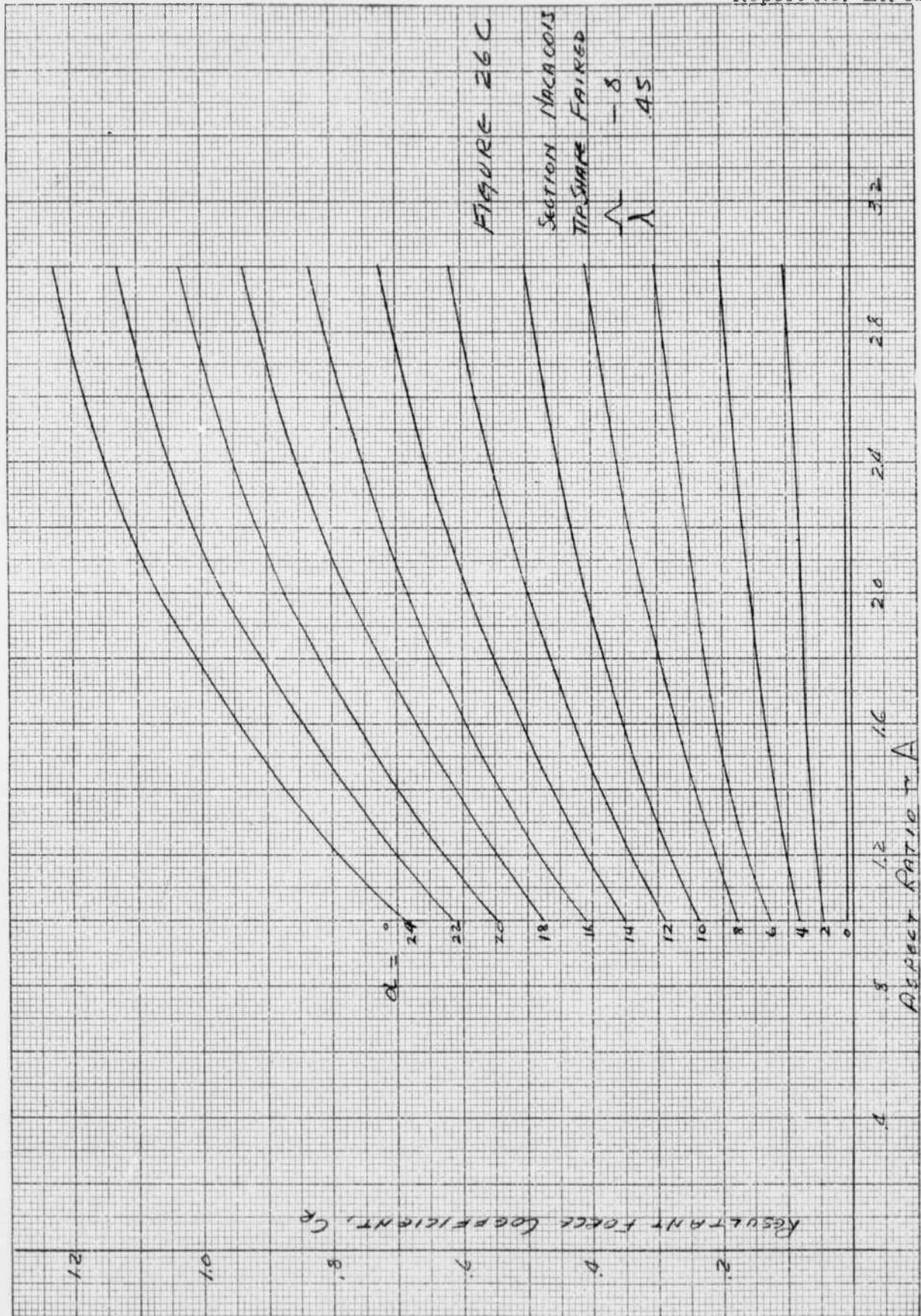


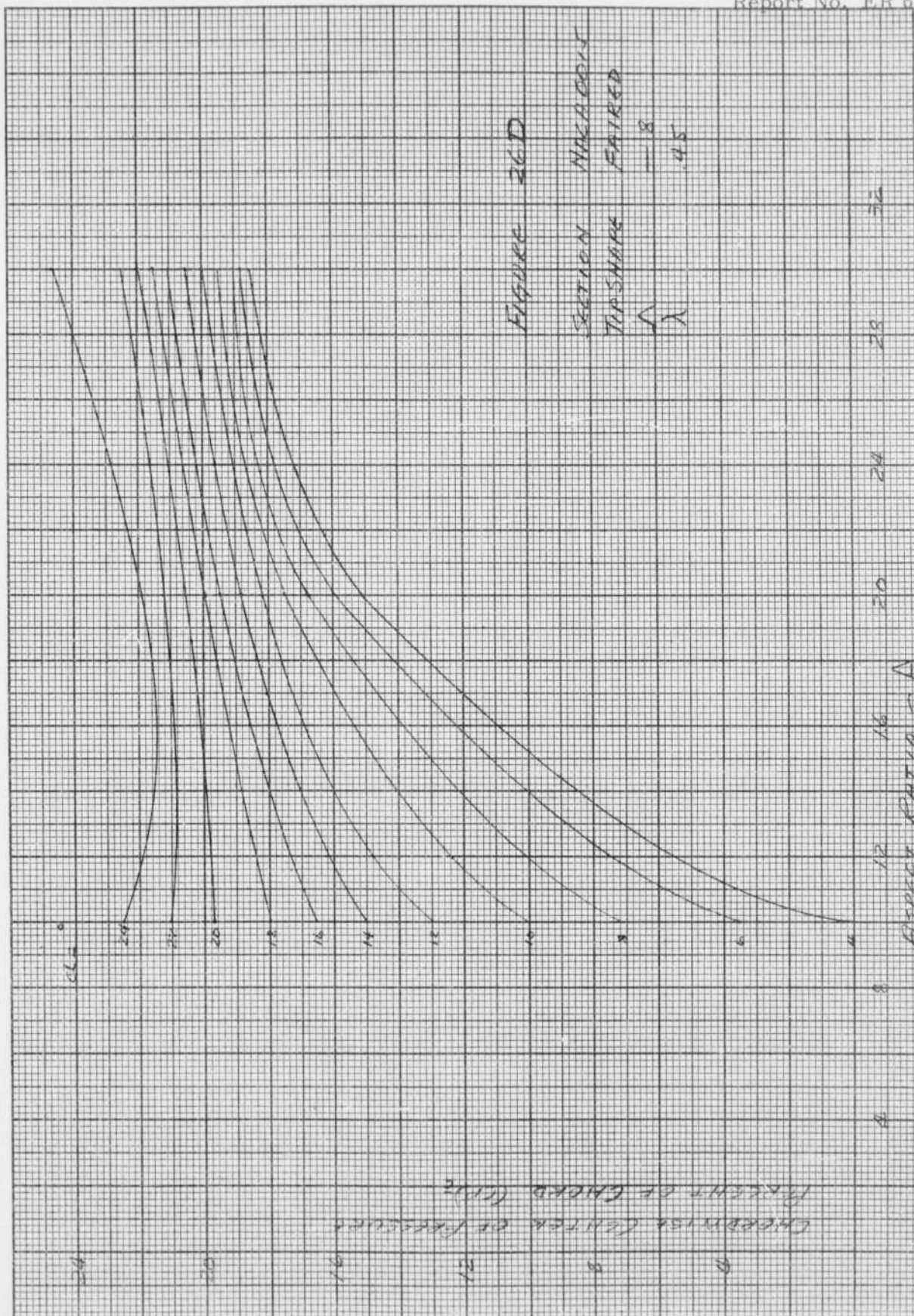


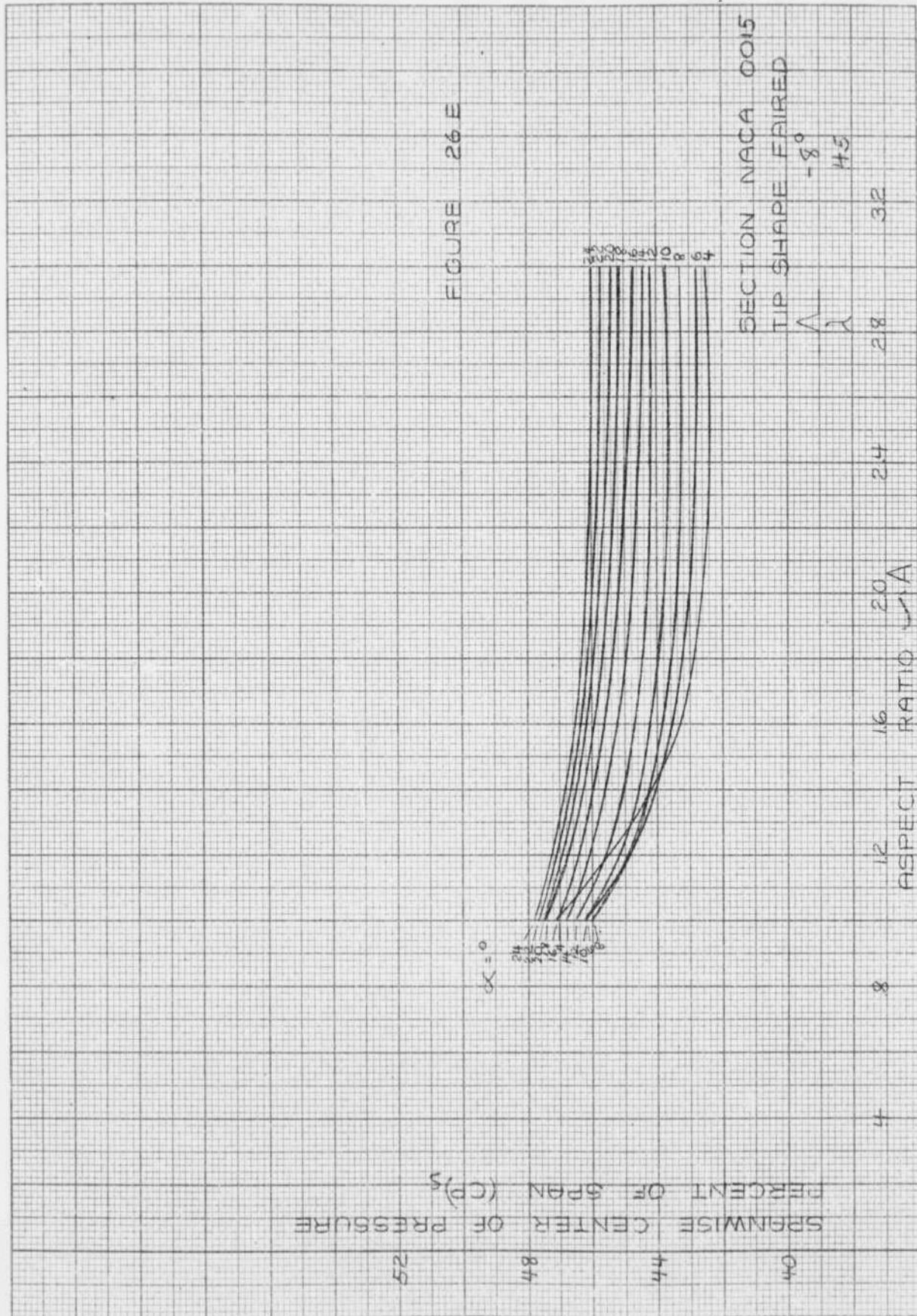


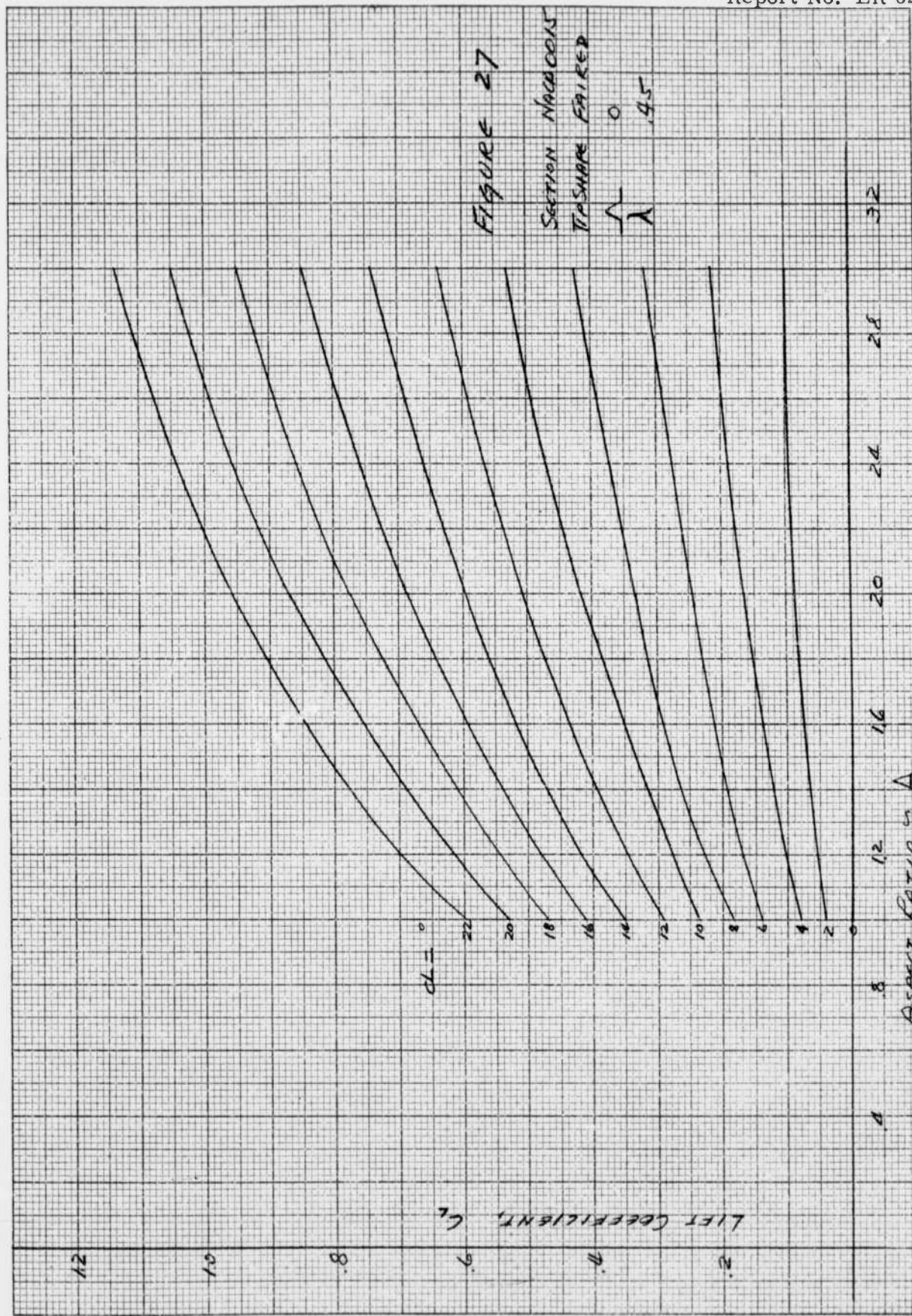


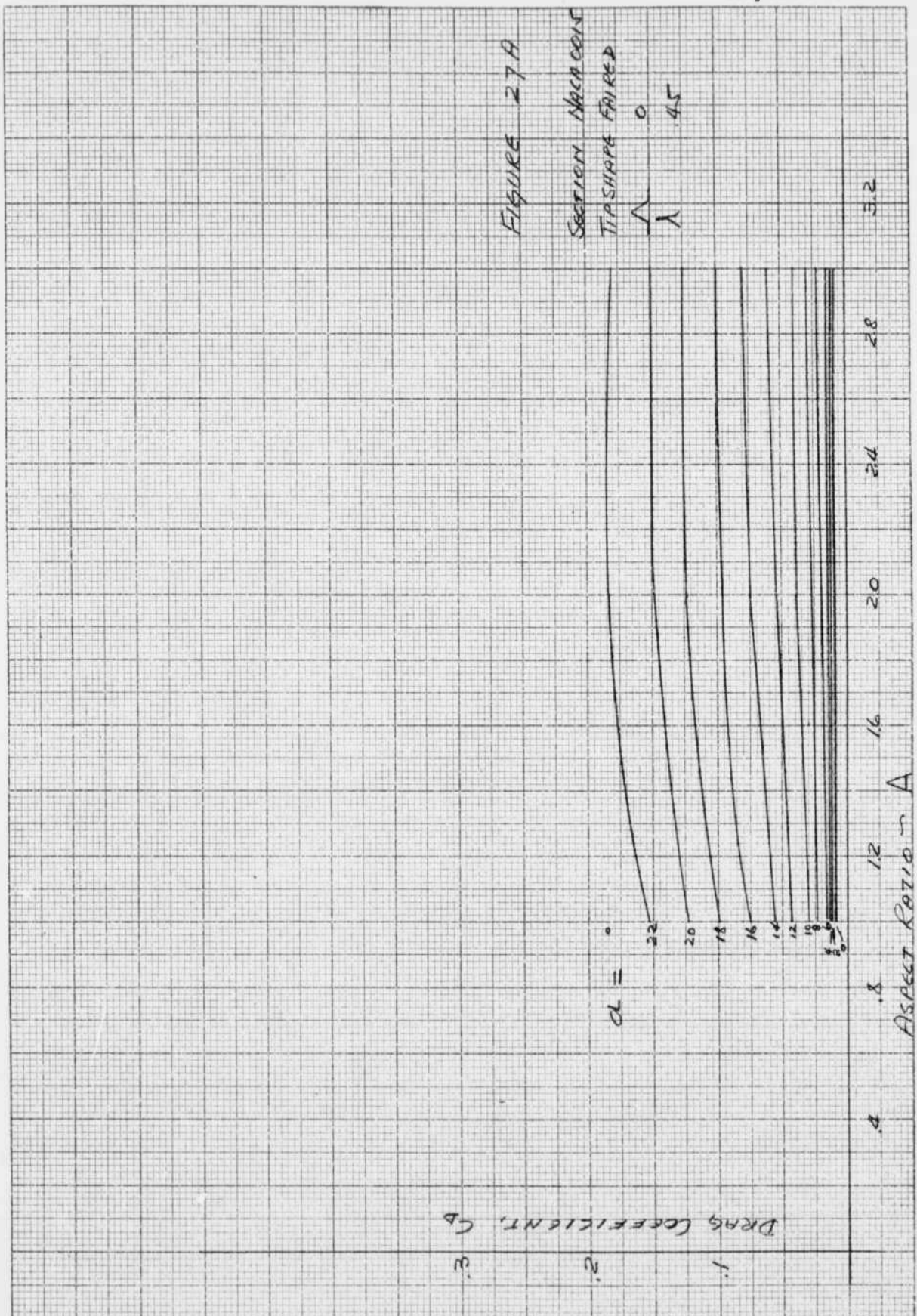


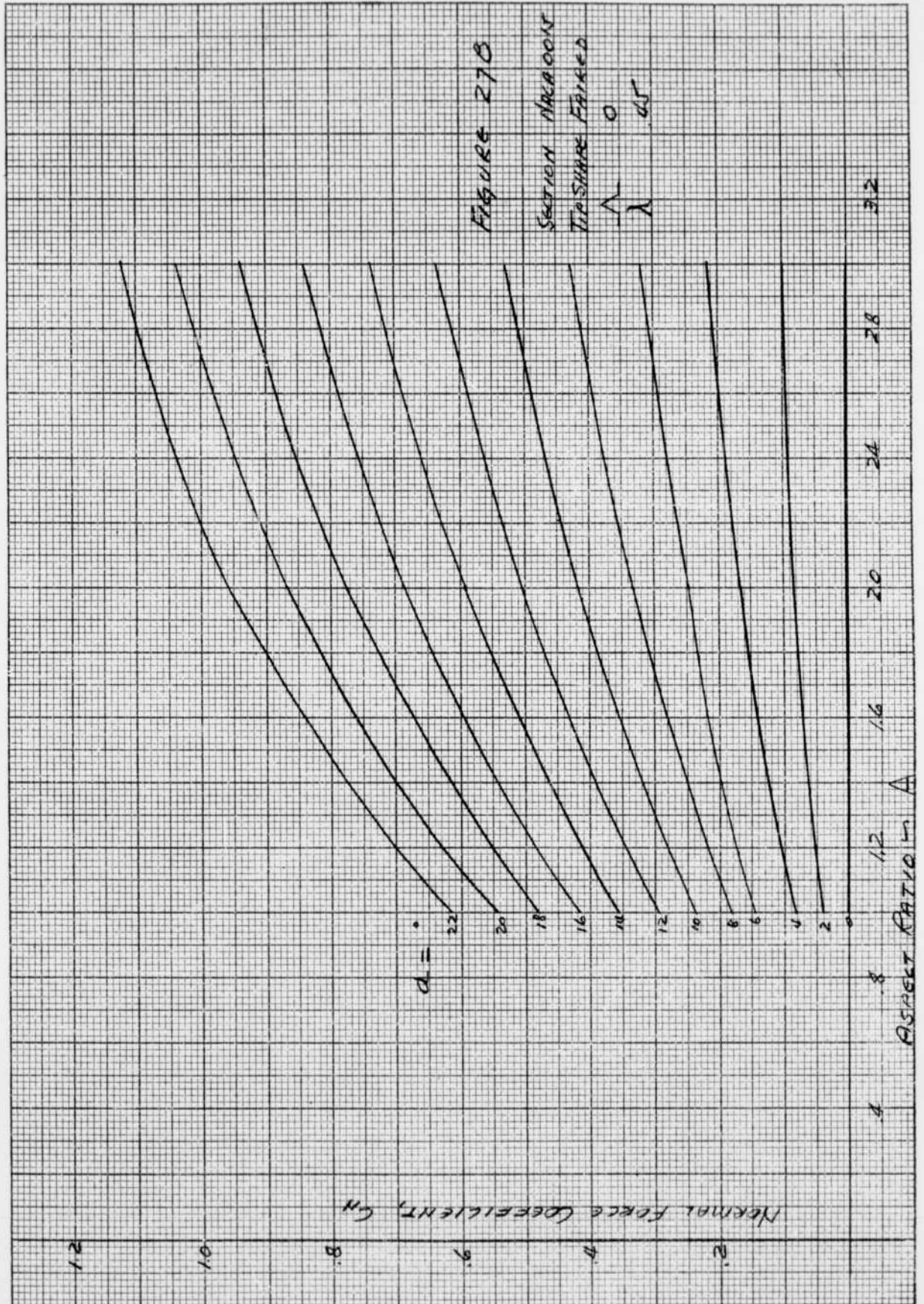


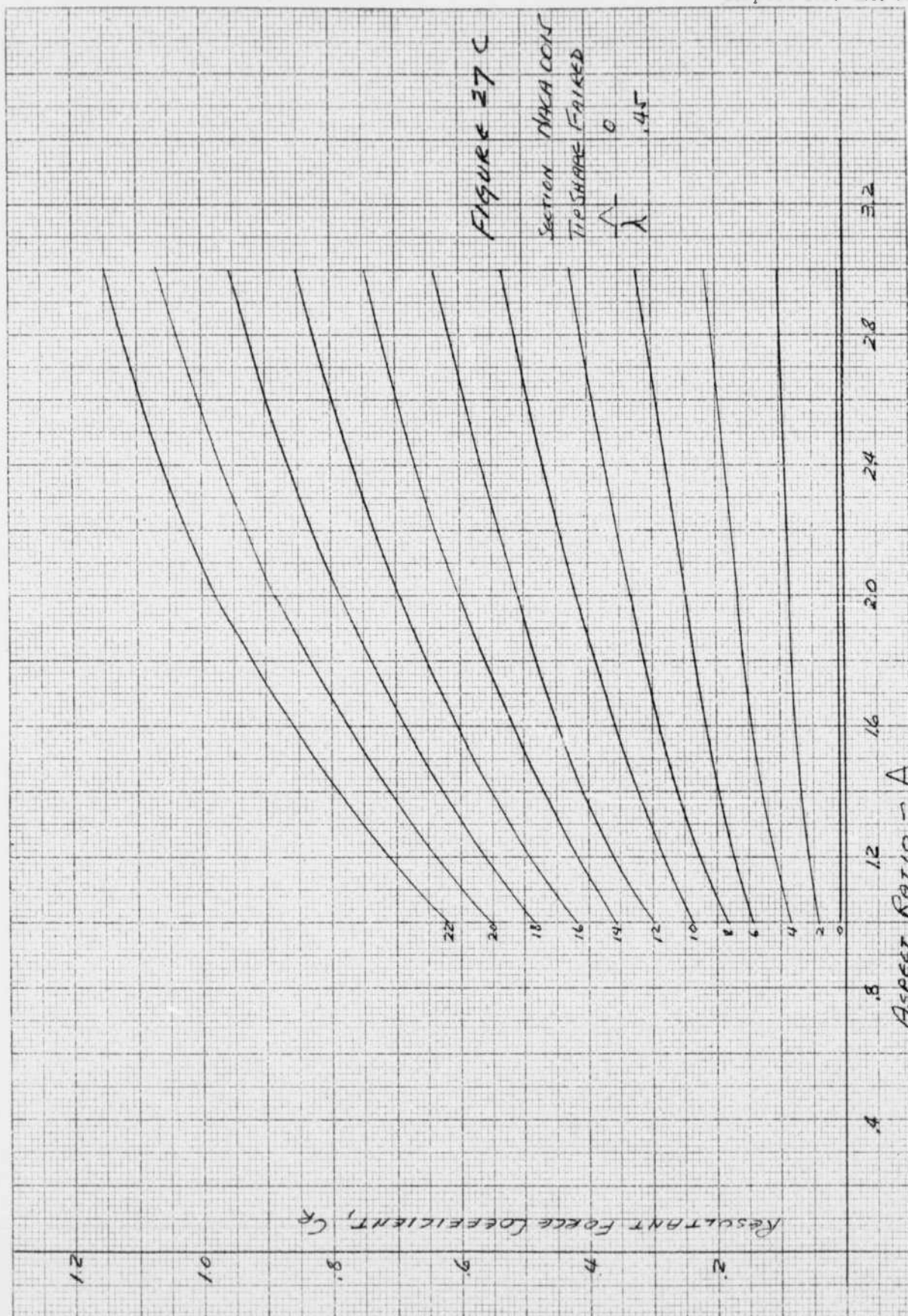


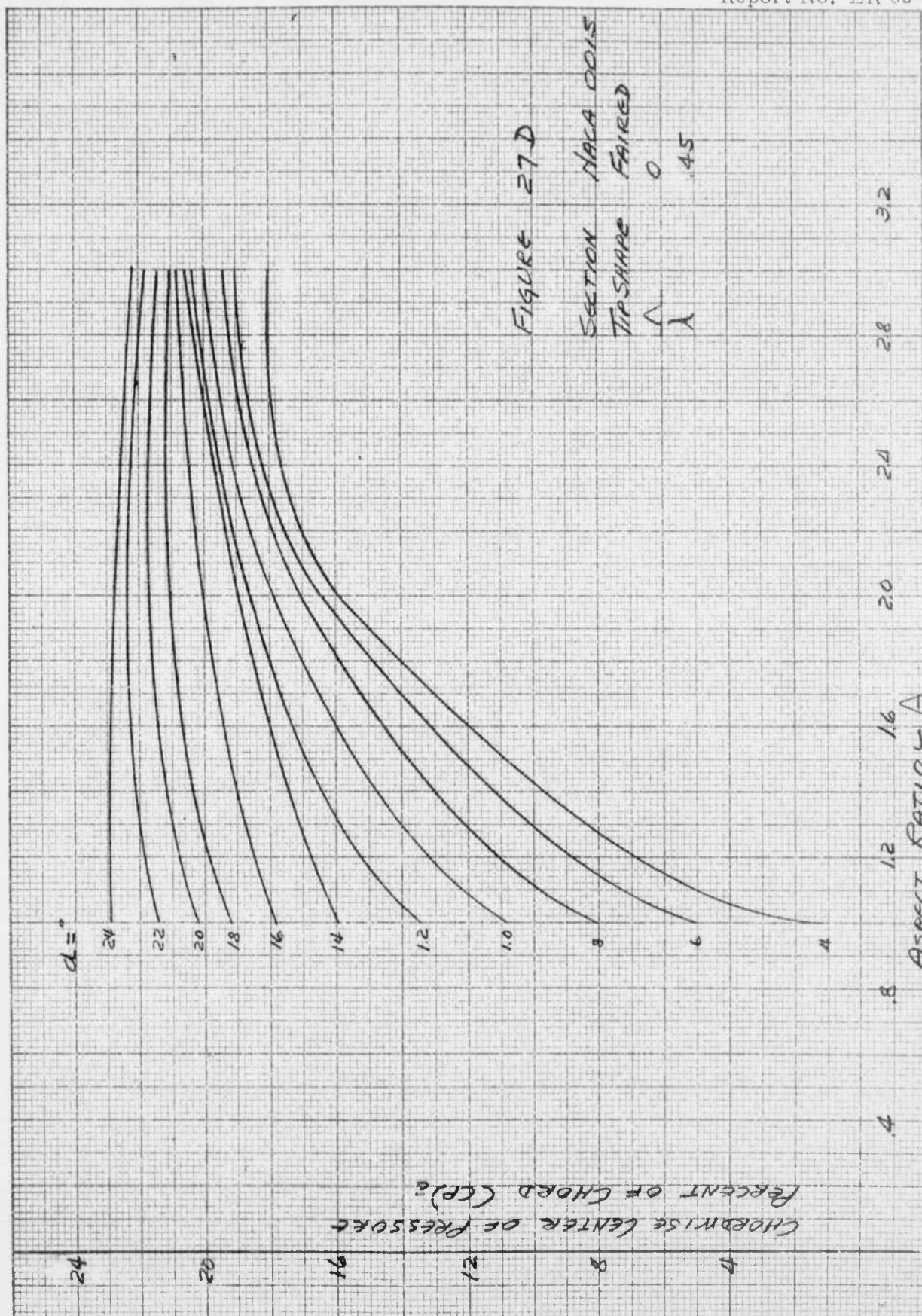


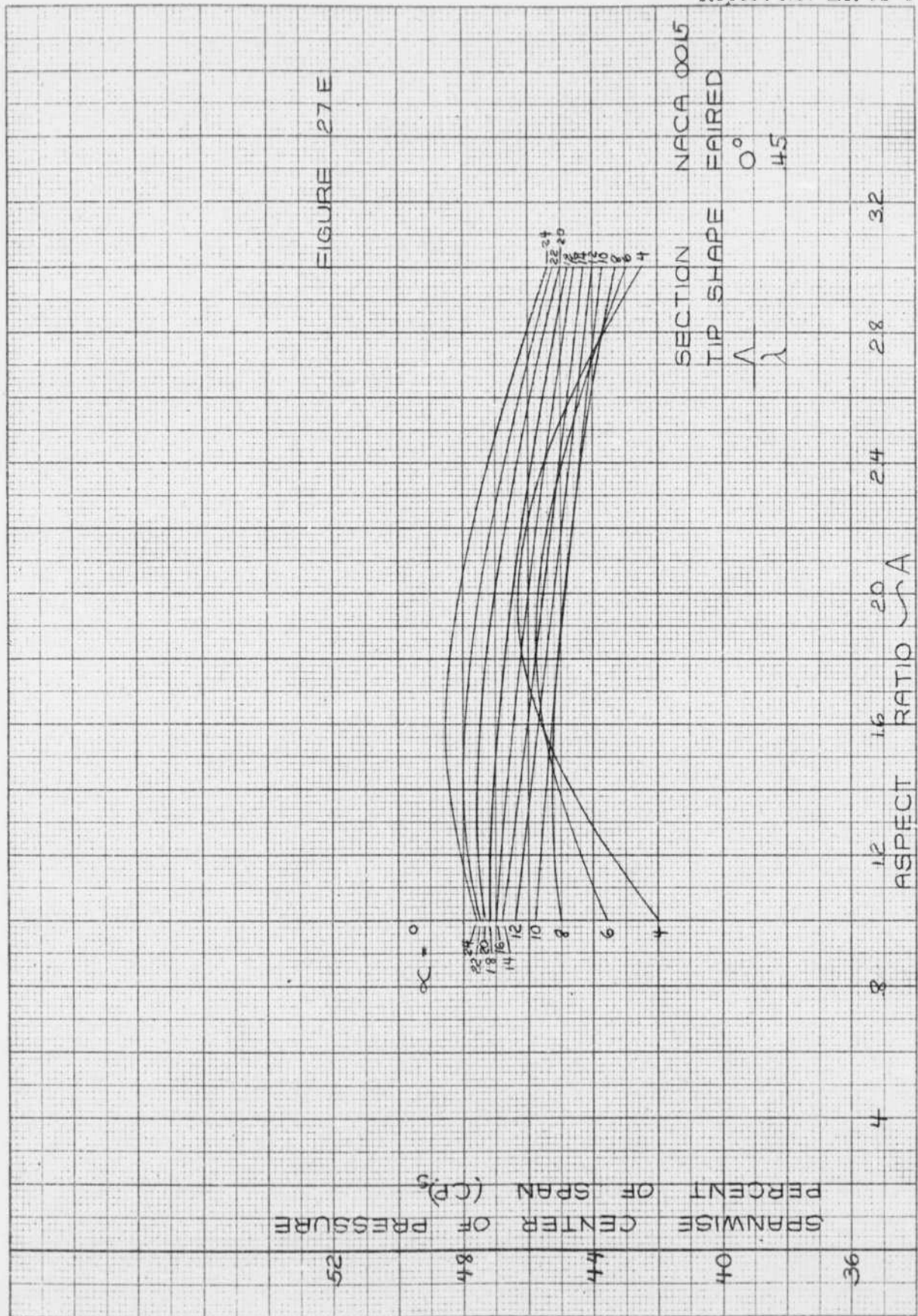


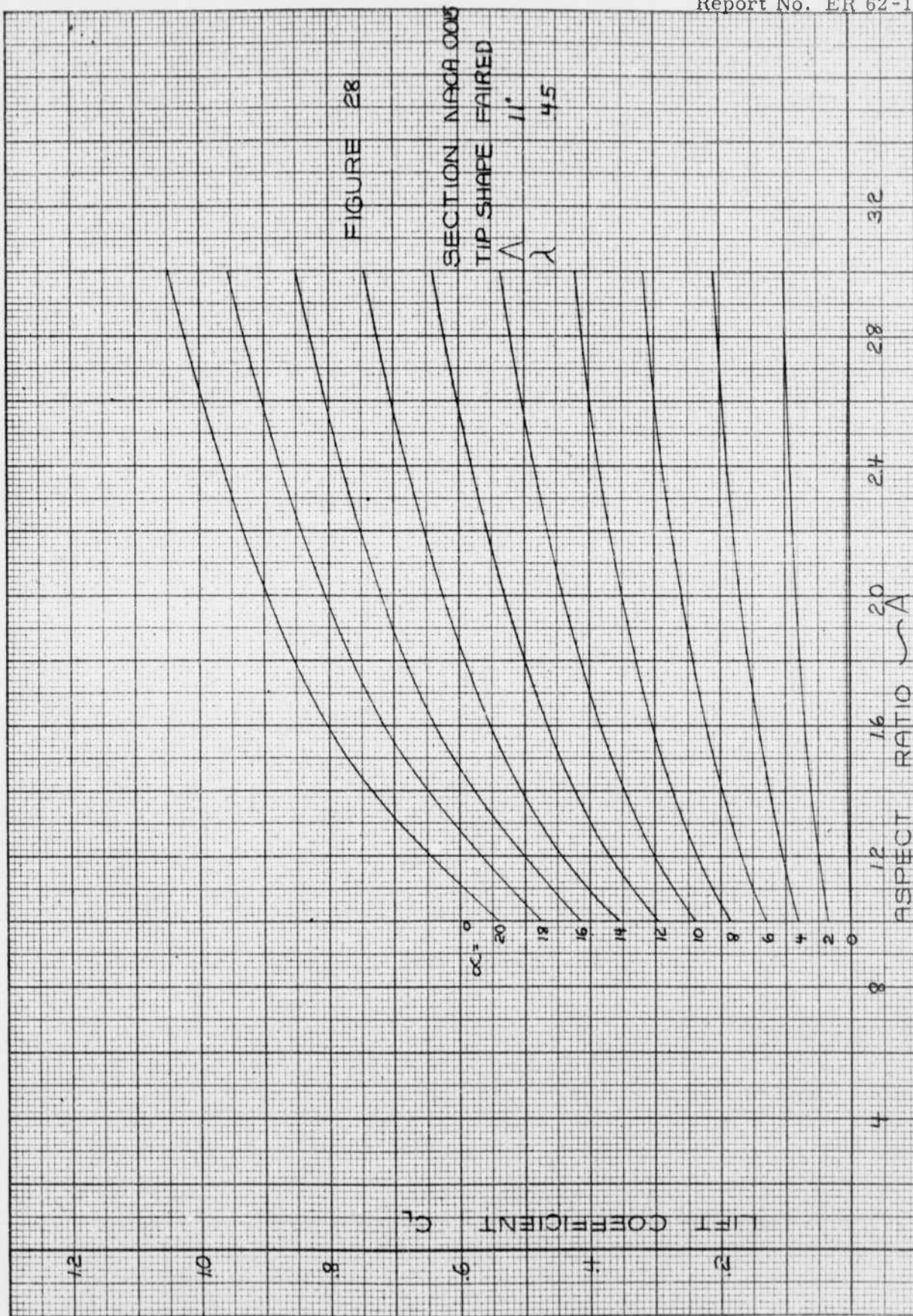


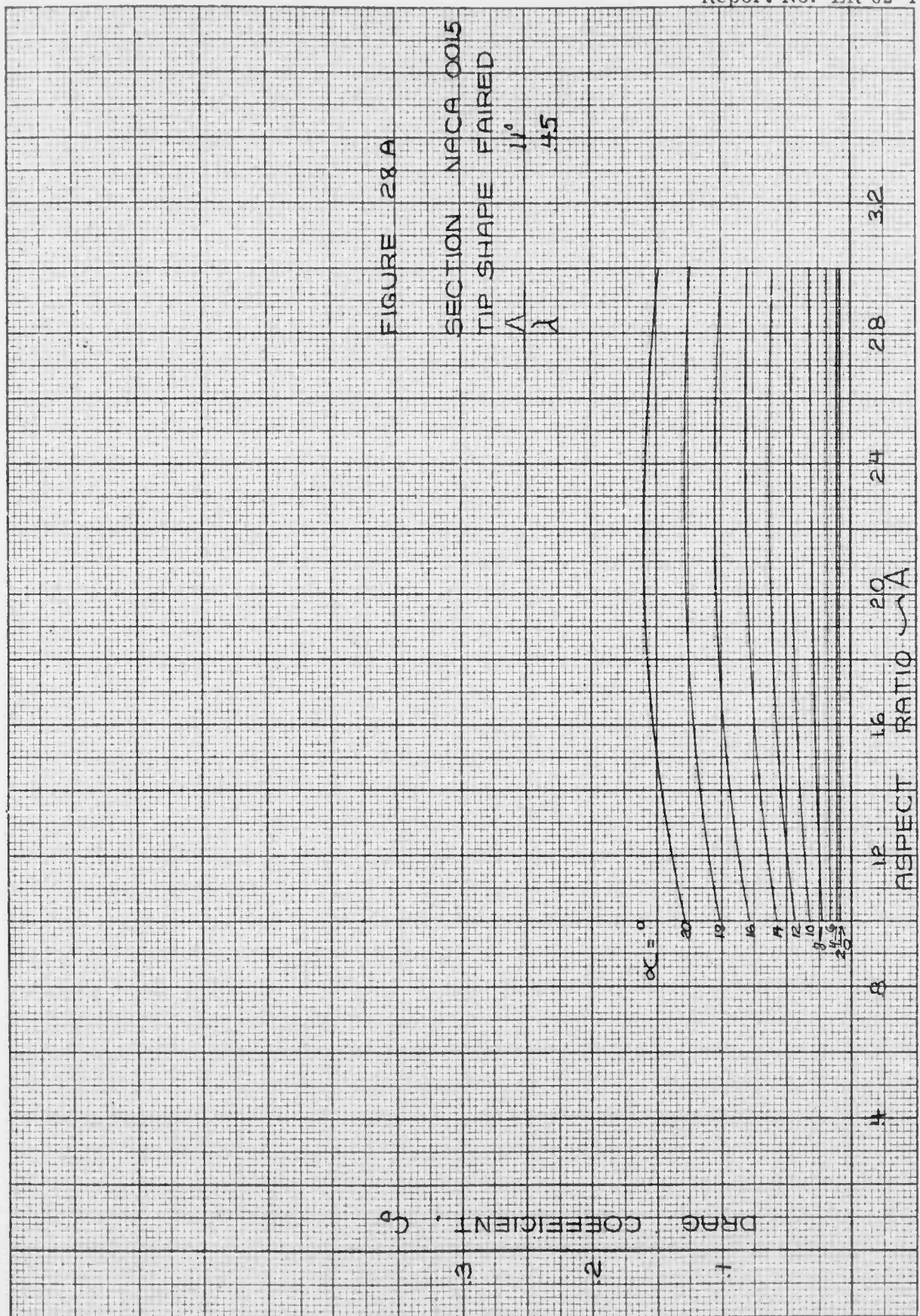


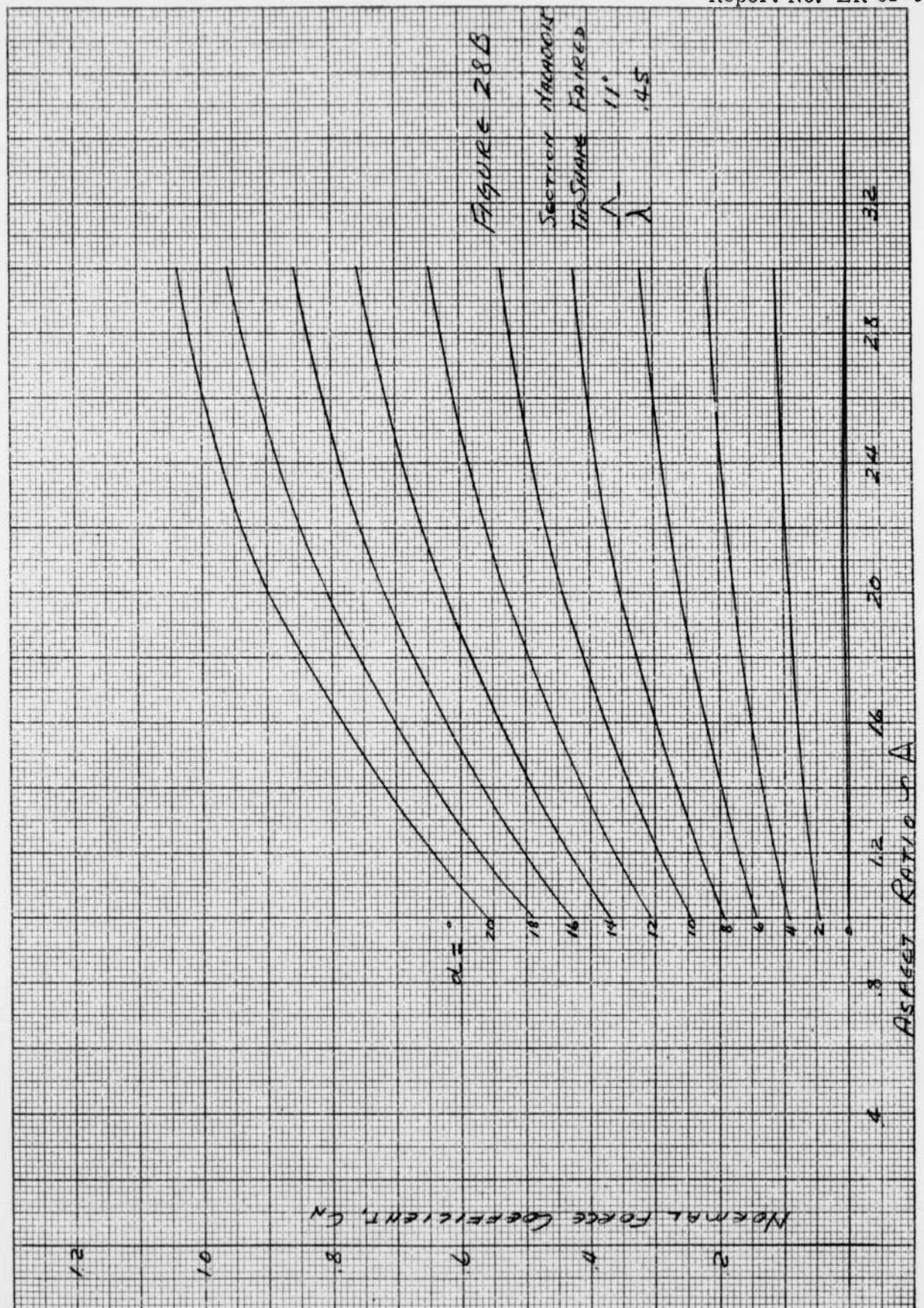


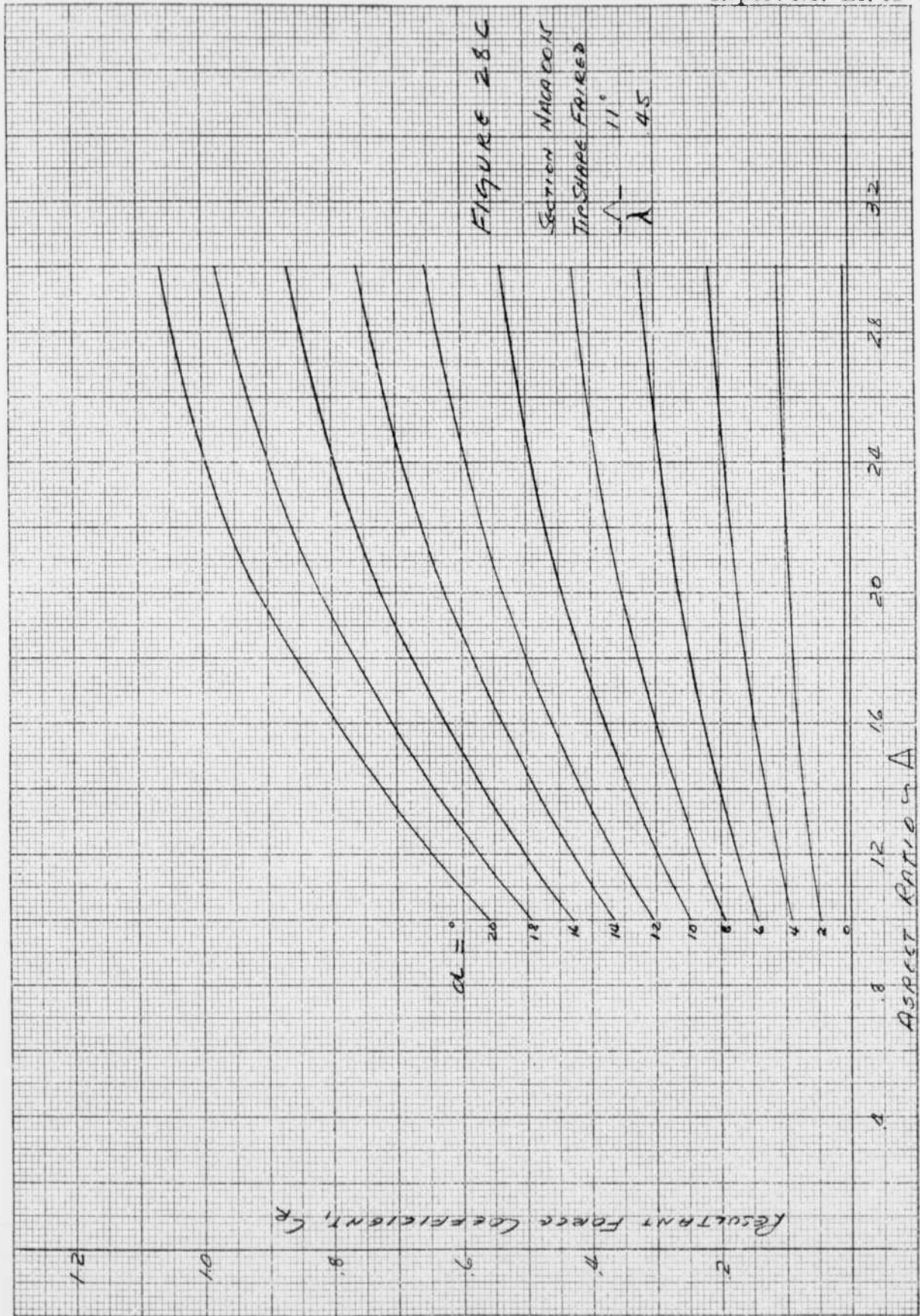


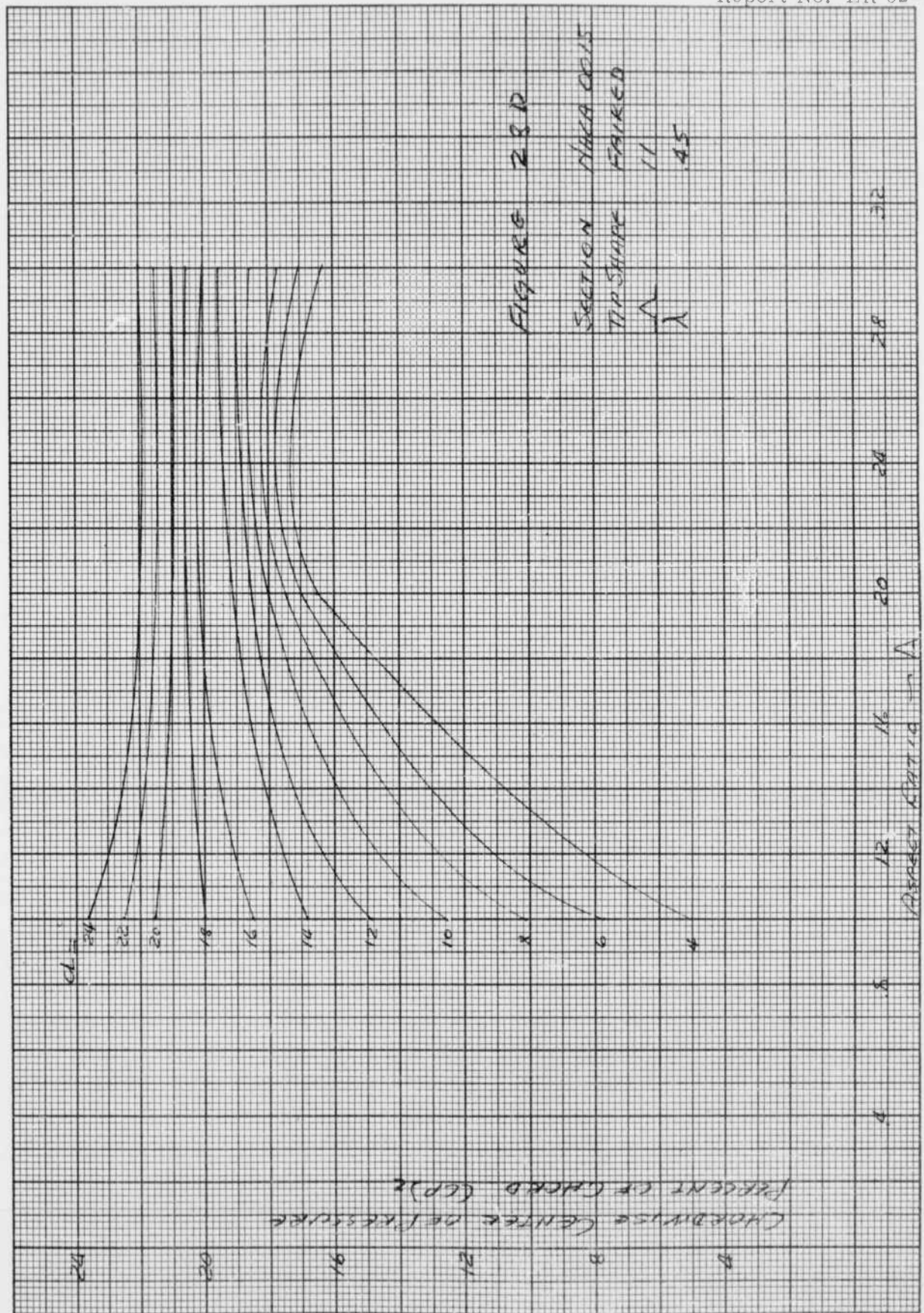


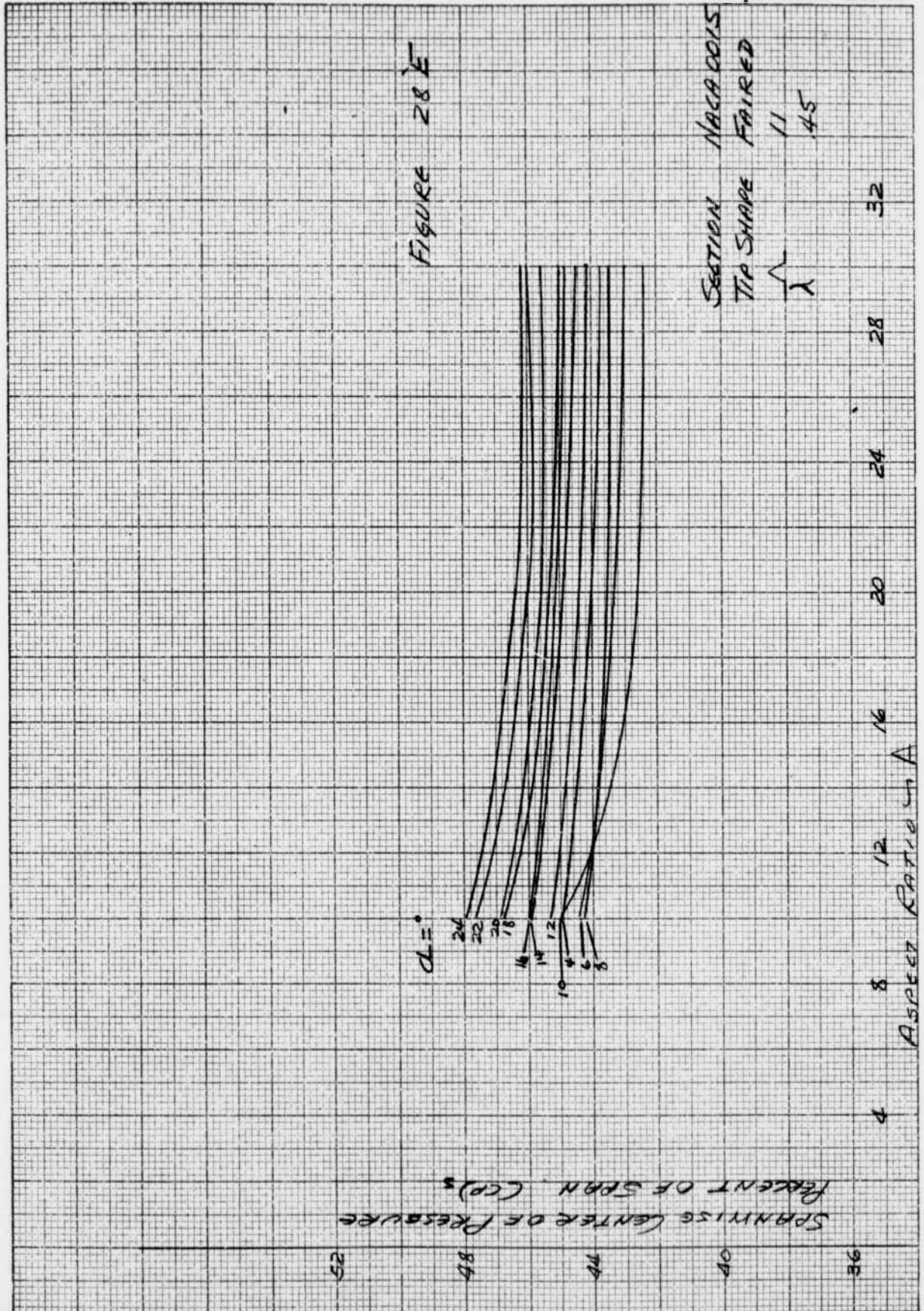


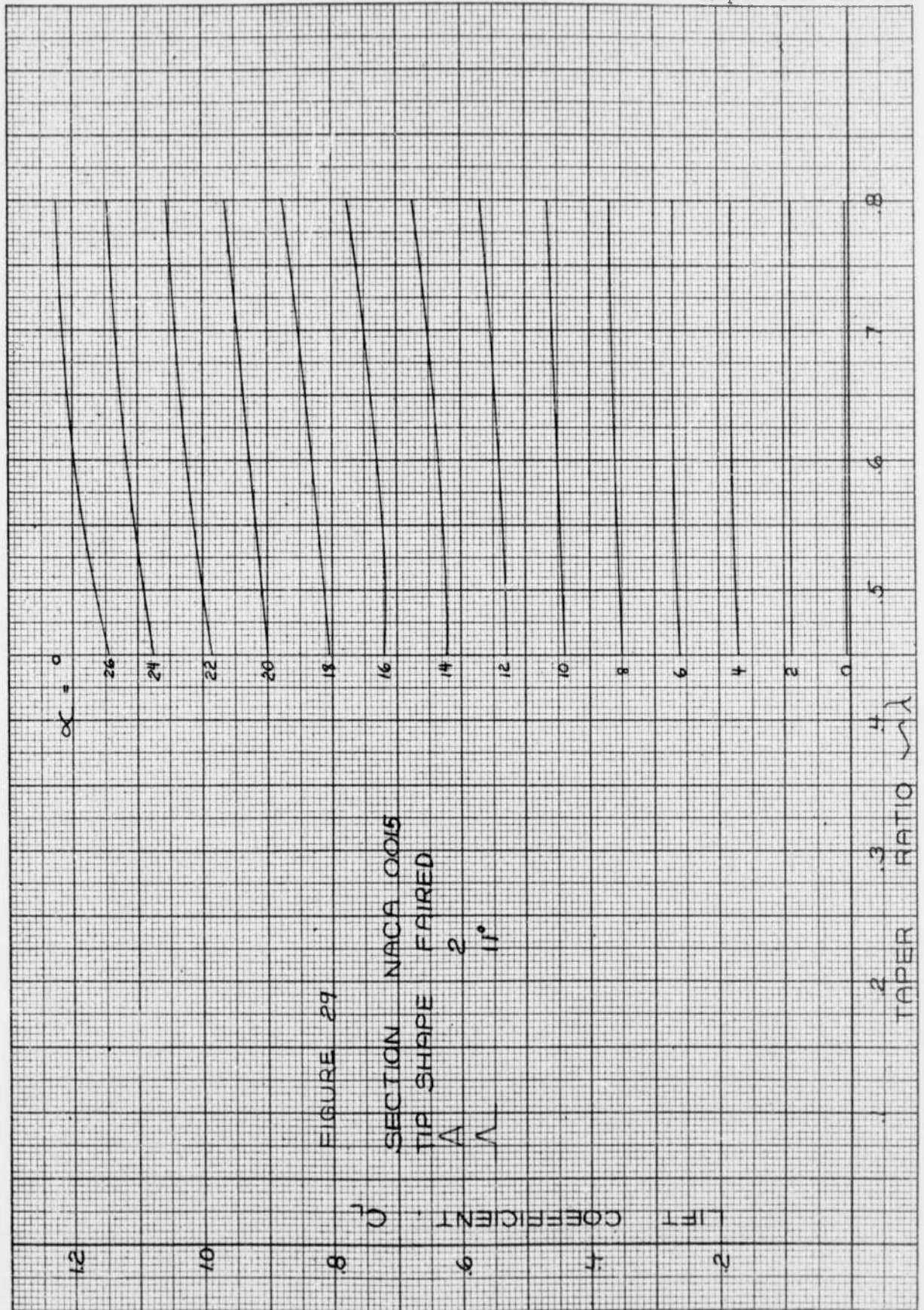


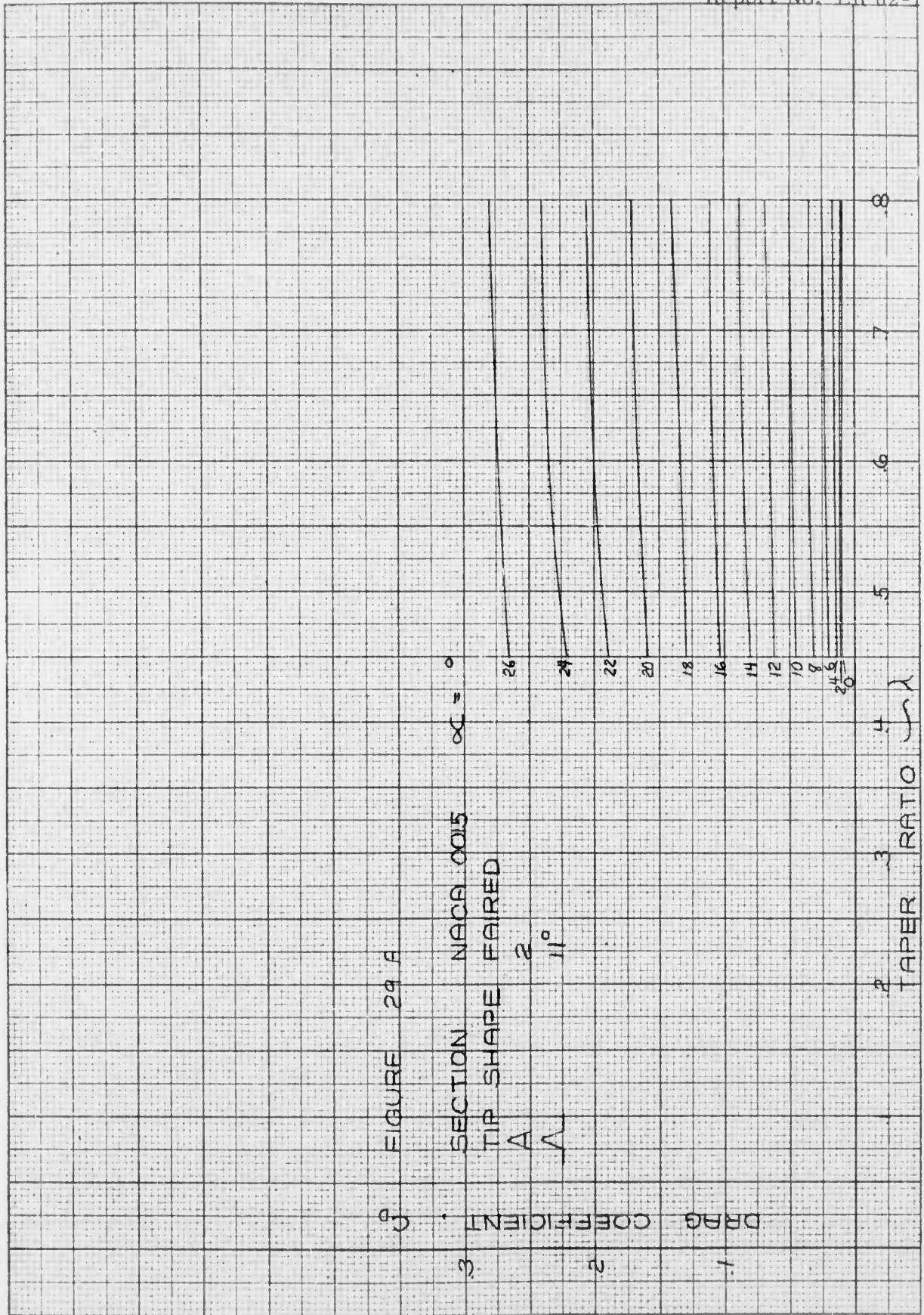


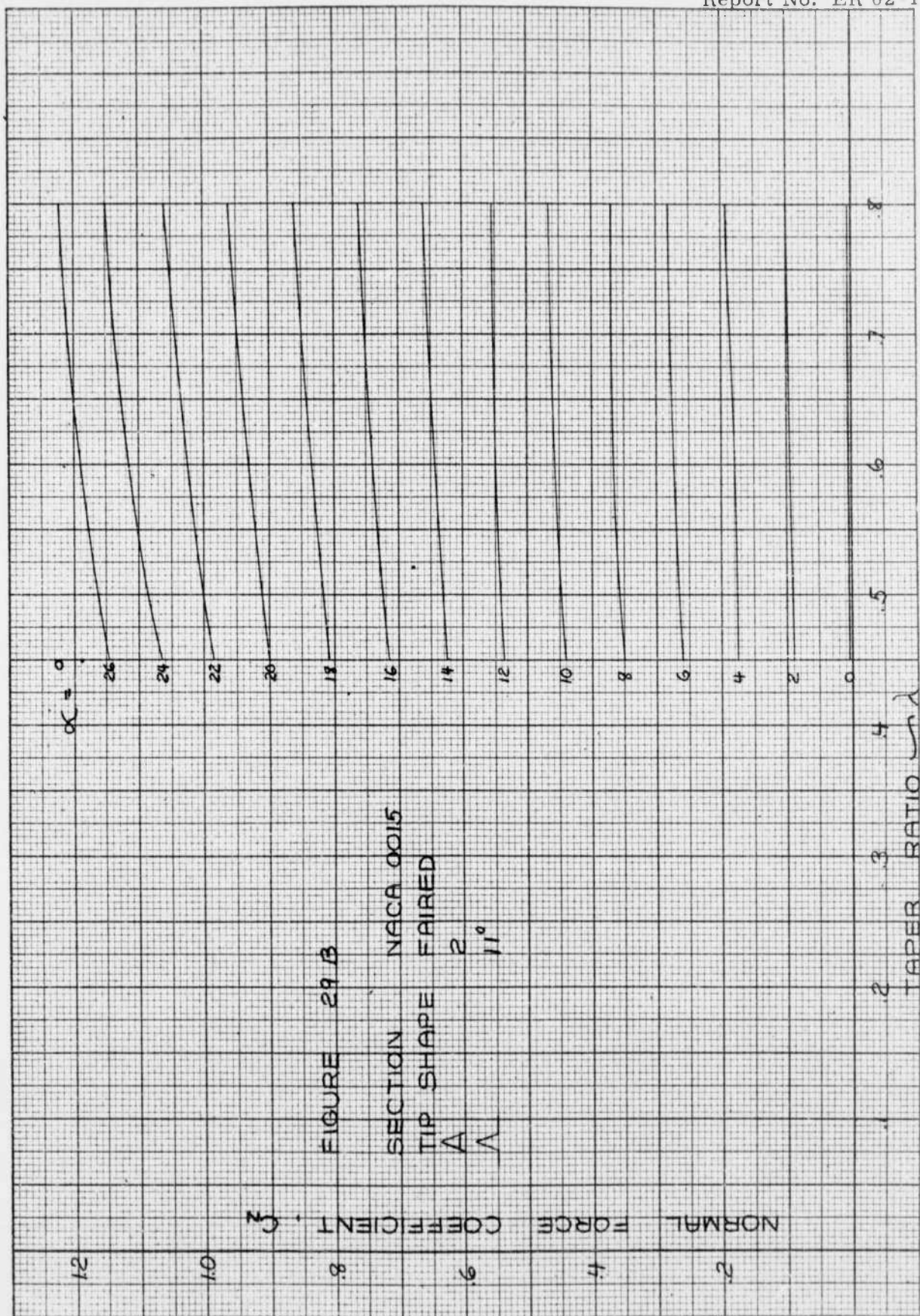


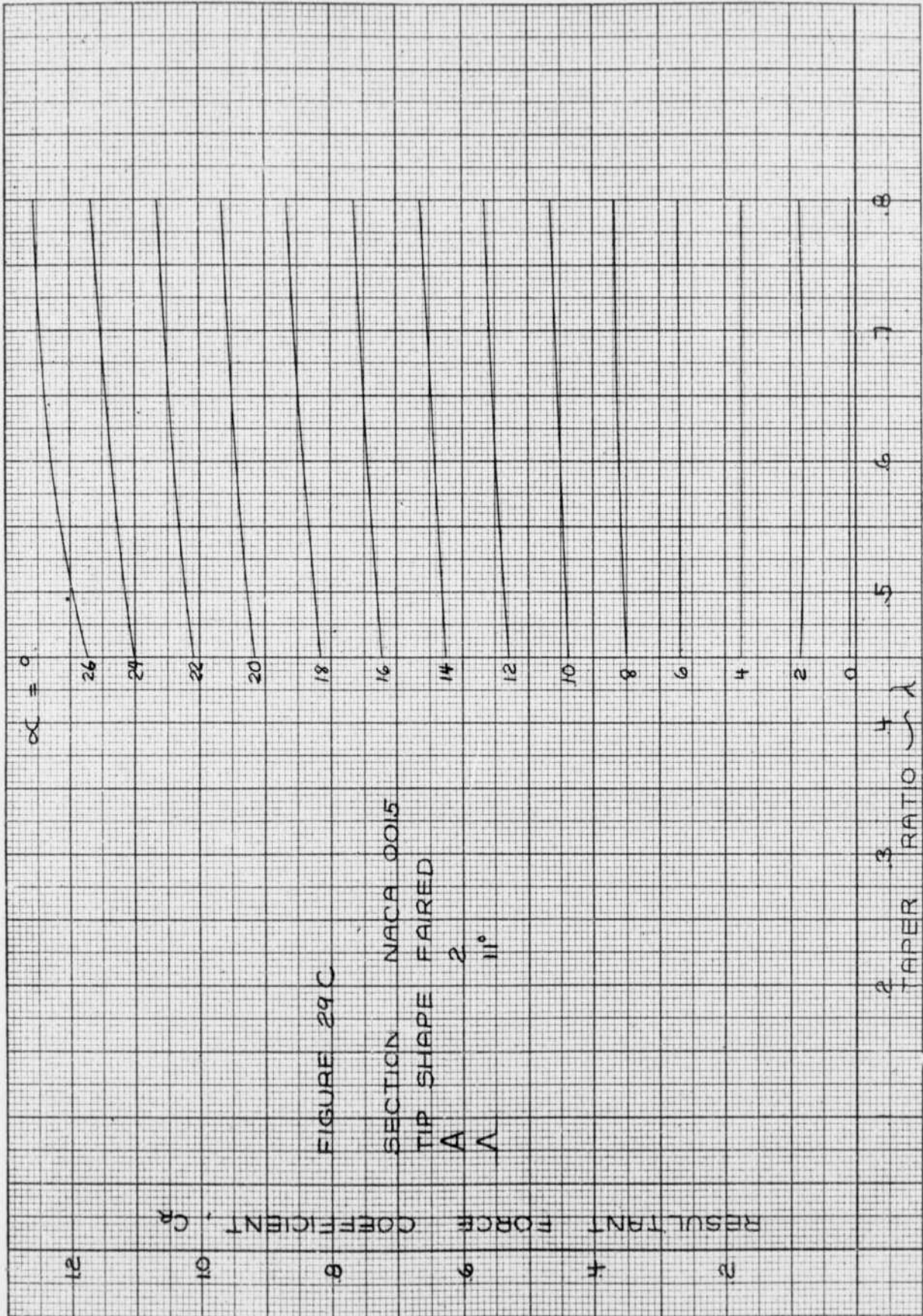












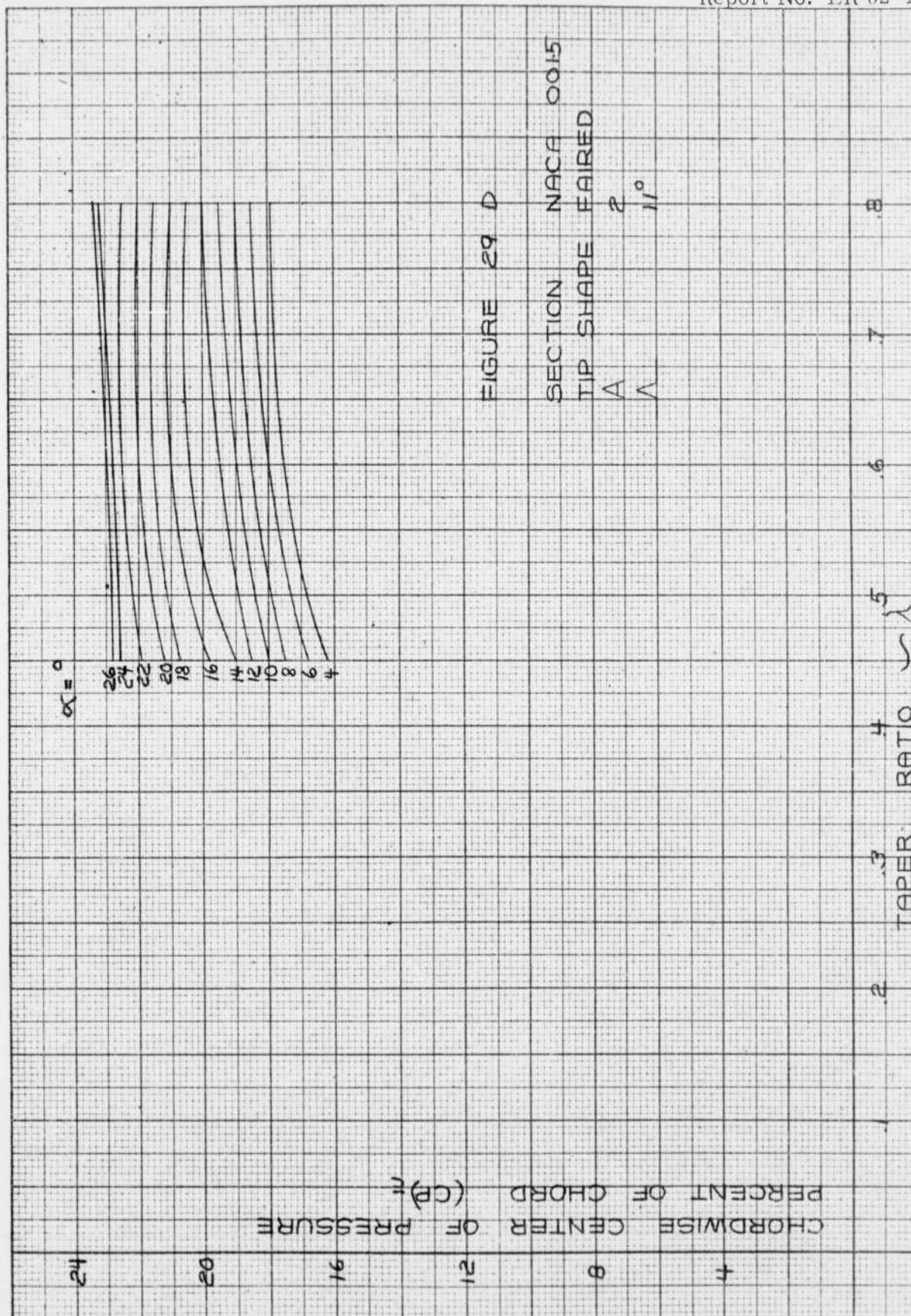


FIGURE 29 F

SPANWISE CENTER OF PRESSURE
OF SPAN (CP)_s

25 40 55 70

25
30
35

$\alpha_c = 0^\circ$

26 24 22 20 18 16 14 12 10 8 6 4

SECTION NACA 0015
TIP SHAPE FAIRED

A Λ

2 11°

7

8

5

4

2

3

4

5

4

7

8

9

10

11

12

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14

15

16

17

18

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285

</

FIGURE 30

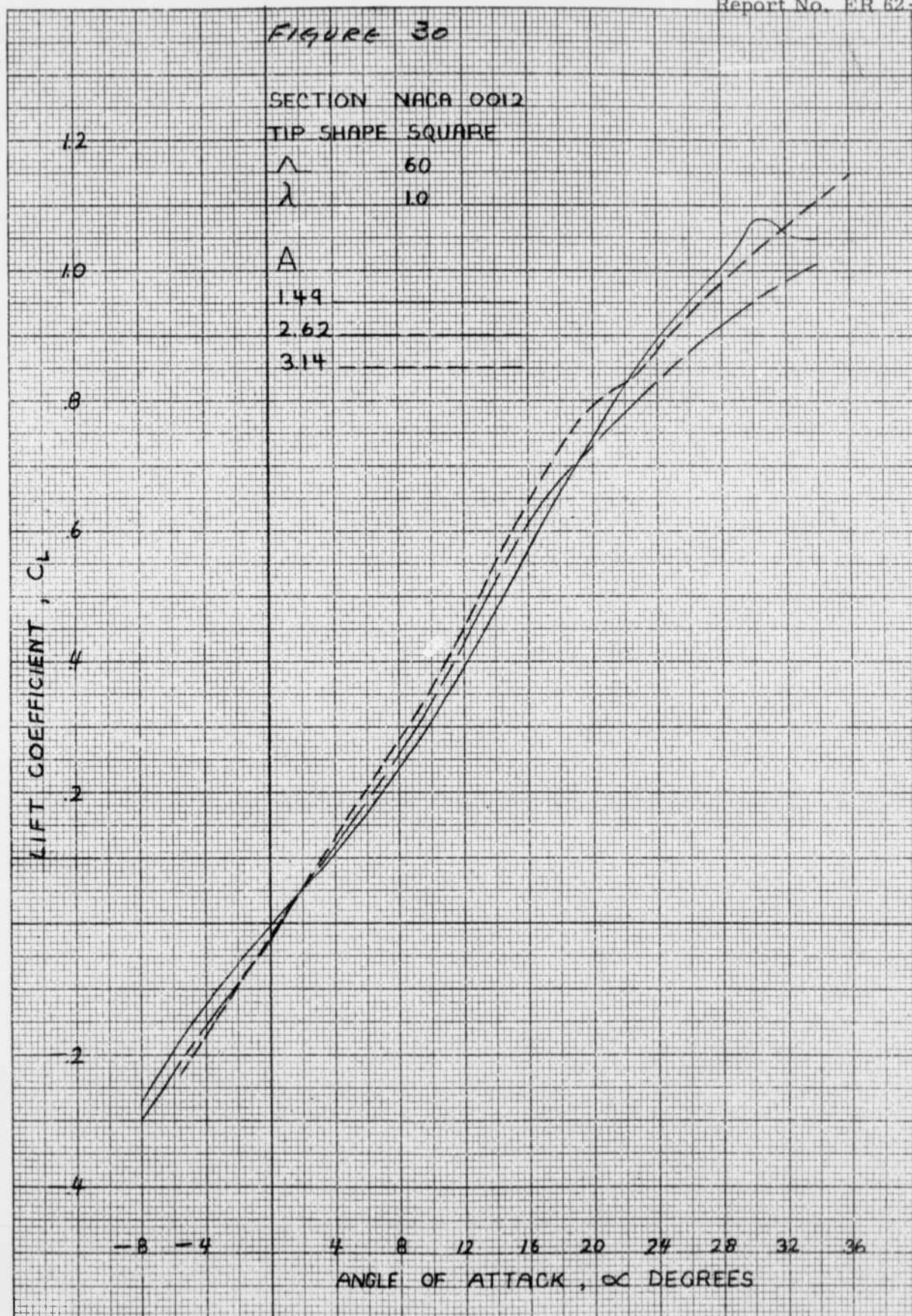
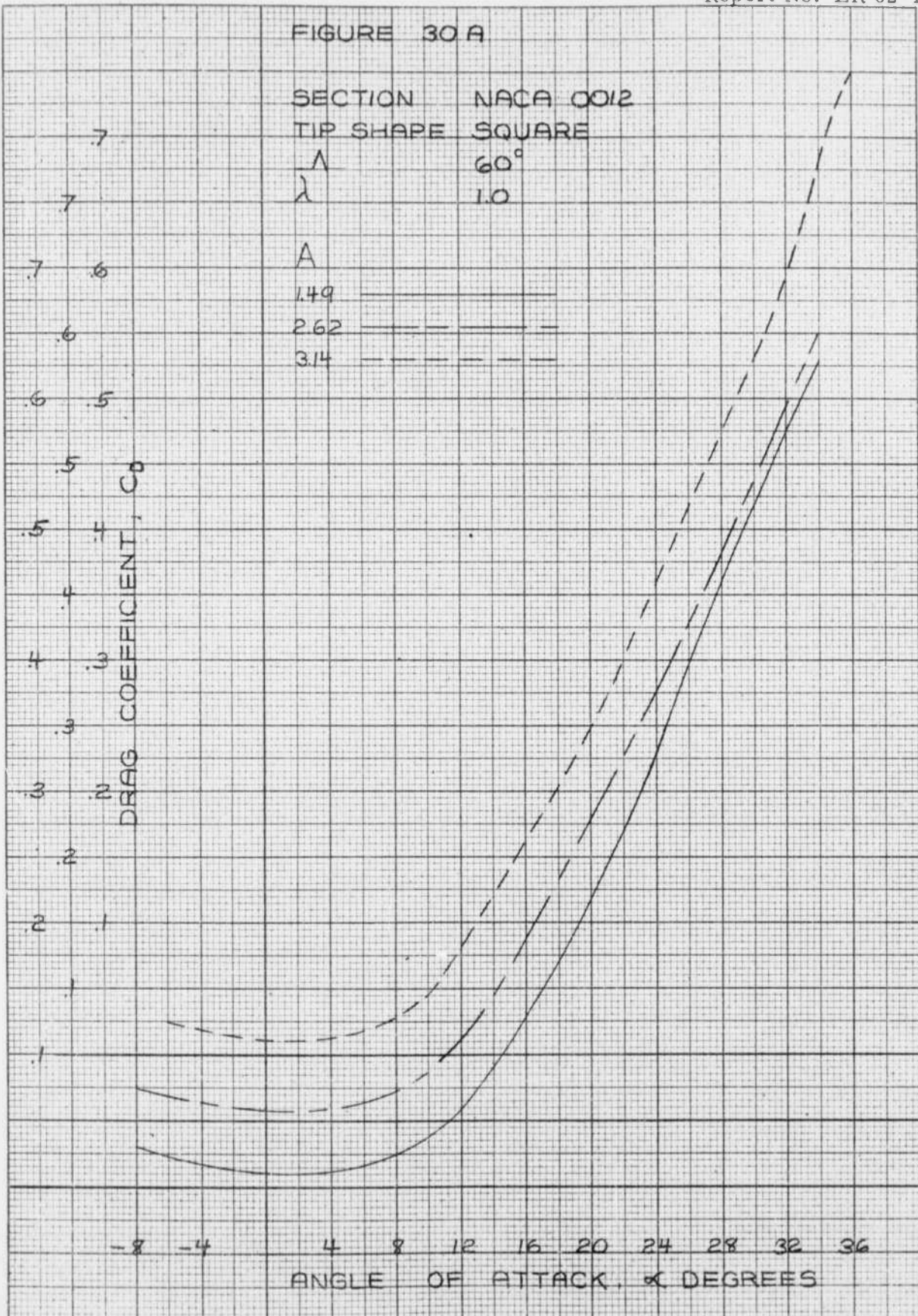


FIGURE 30 A



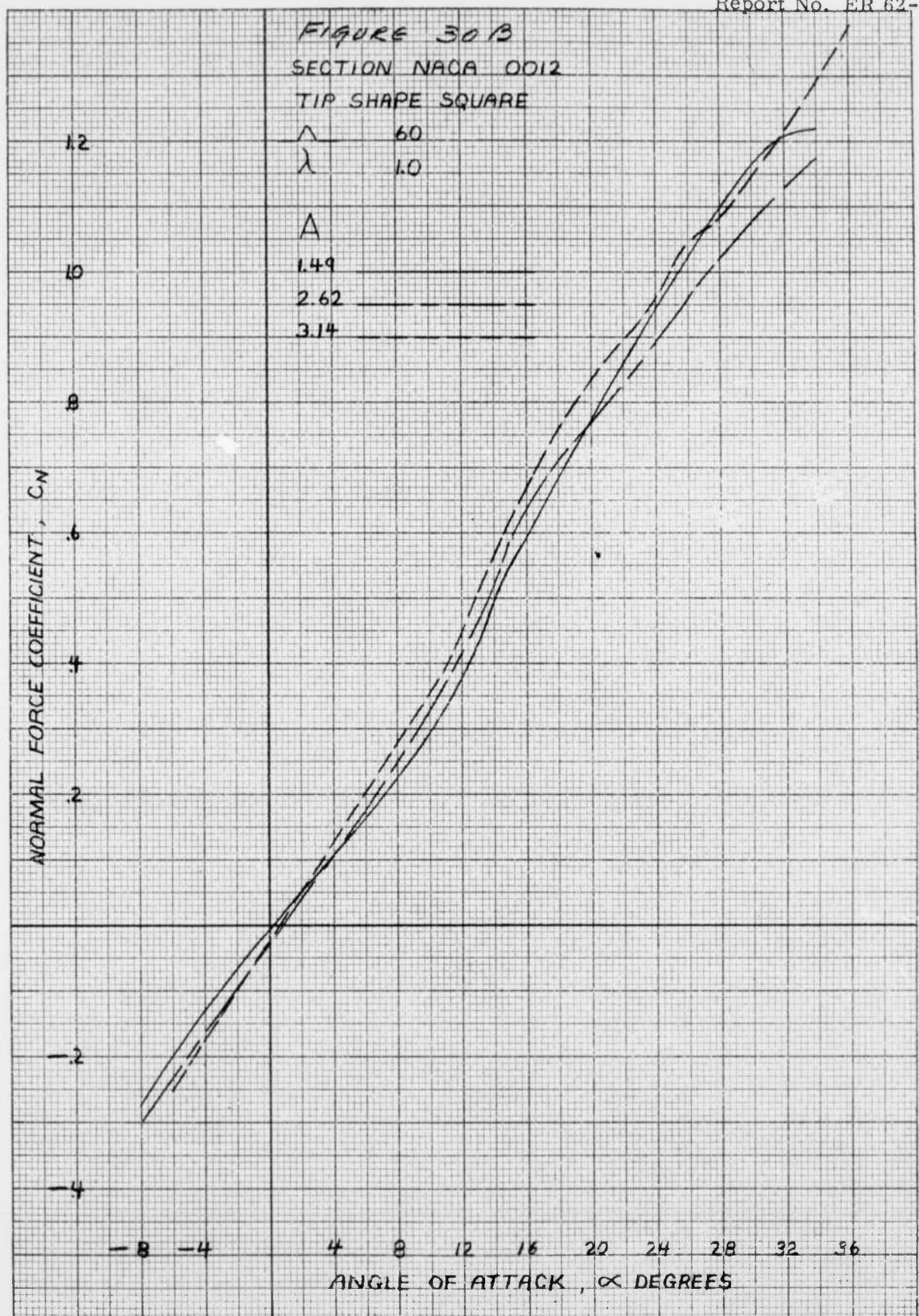


FIGURE 30C

SECTION NACA 0012
TIP SHAPE SQUARE

Λ 60
 λ 1.0

A
1.49
2.62
3.14

1.2

1.0

RESULTANT FORCE COEFFICIENT, C_R

0.8

0.6

0.4

0.2

0

-0.2

-0.4

-0.6

-0.8

-8

-4

4

8

12

16

20

24

28

32

36

ANGLE OF ATTACK, α DEGREES

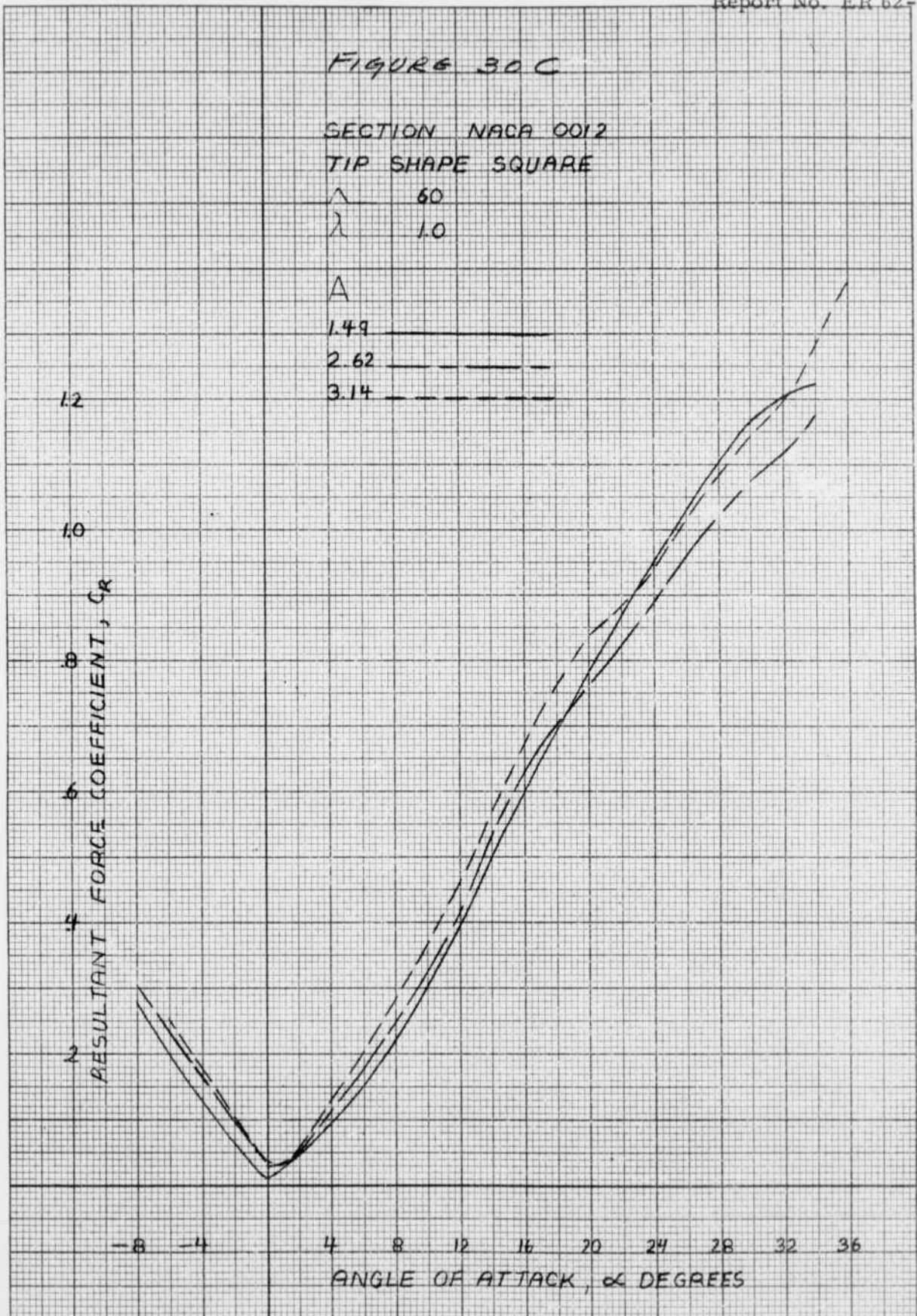


FIGURE 30 D

SECTION NACA 0012

TIP SHAPE SQUARE

^ 60

λ 10

A

1.49

2.62

3.14

CHORDWISE CENTER OF PRESSURE
PERCENT OF CHORD (C.P.)

30

20

10

-8 -4

4

8

12

16

20

24

28

32

36

ANGLE OF ATTACK, α , DEGREES

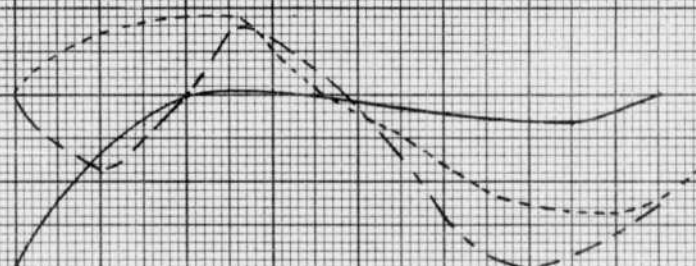


FIGURE 31

SECTION NACA 0012
TIP SHAPE SQUARE
 Δ 1.33

λ	Δ	
0	66.0	—————
.125	60.2	-----
.25	53.5	-----
.50	36.9	-----

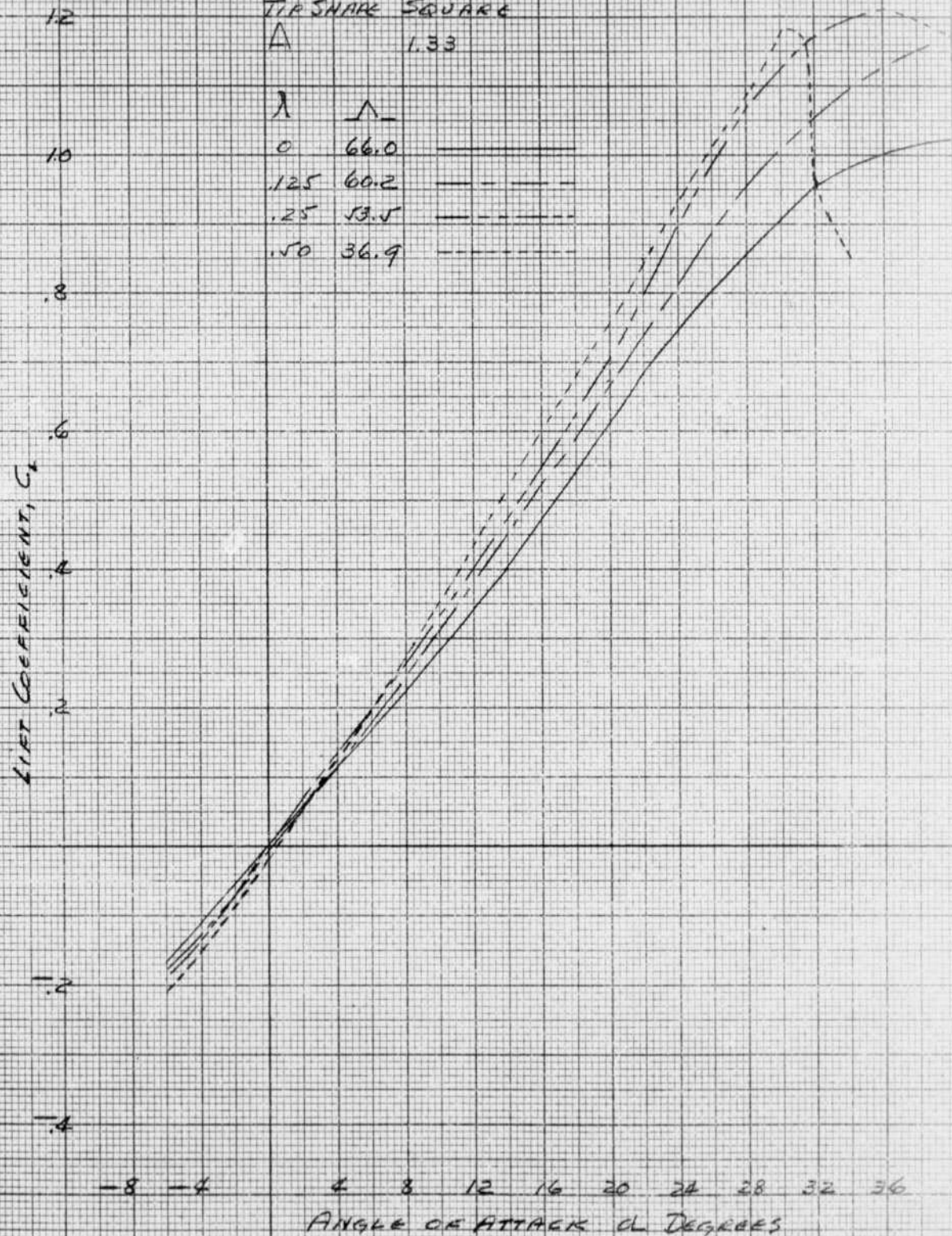


FIGURE 31 A

SECTION NACA 0012
TIP SHAPE SQUARE
A 1.33

λ	Λ
0	66.0°
.125	60.2°
.25	53.5°
.50	36.9°

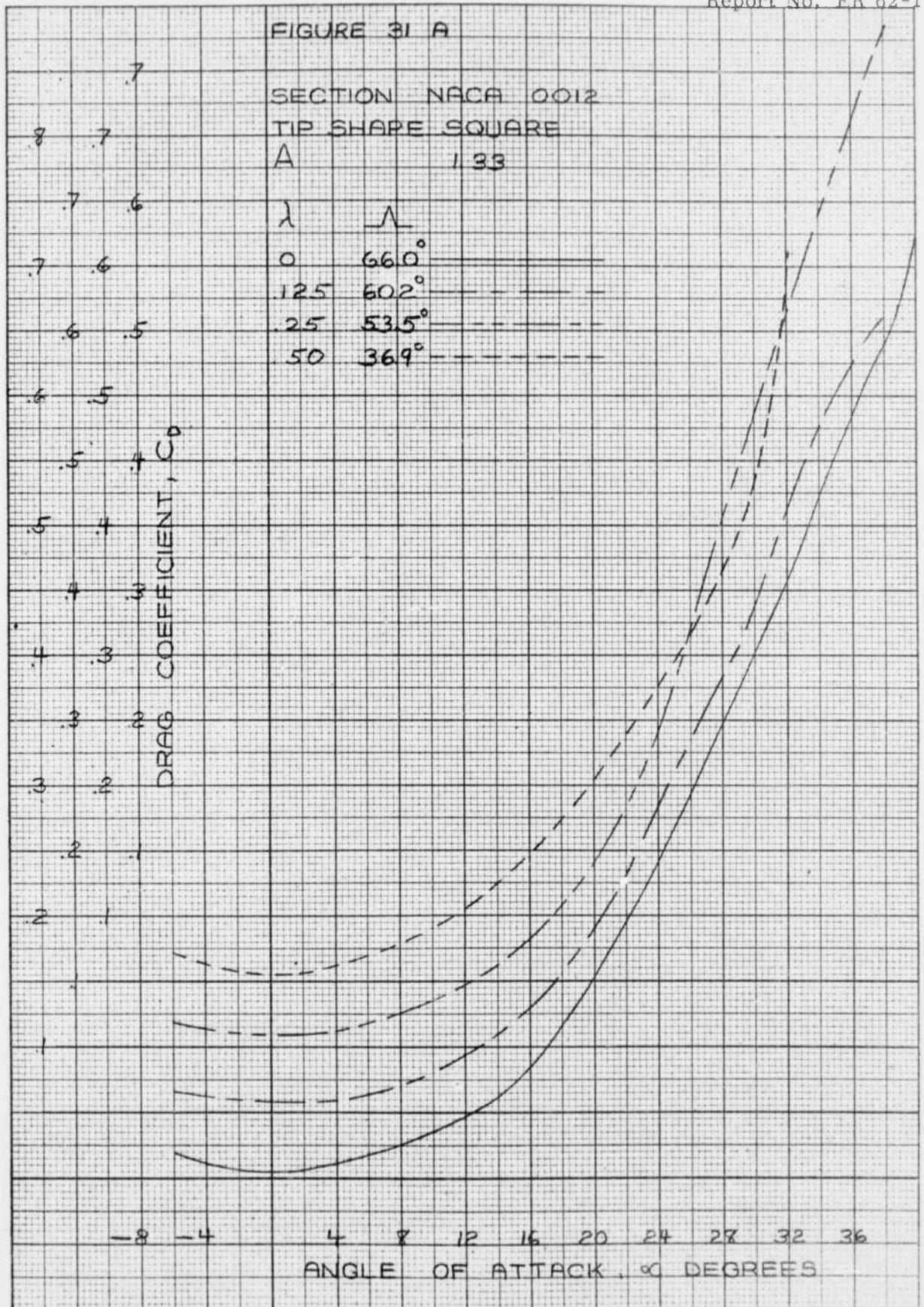


FIGURE 31 B

SECTION NACA 0012
TIP SHAPE SQUARE
A 1.33

λ	Λ	
0	66.0	—————
.125	60.3	-----
.25	53.5	-----
.50	36.9	-----

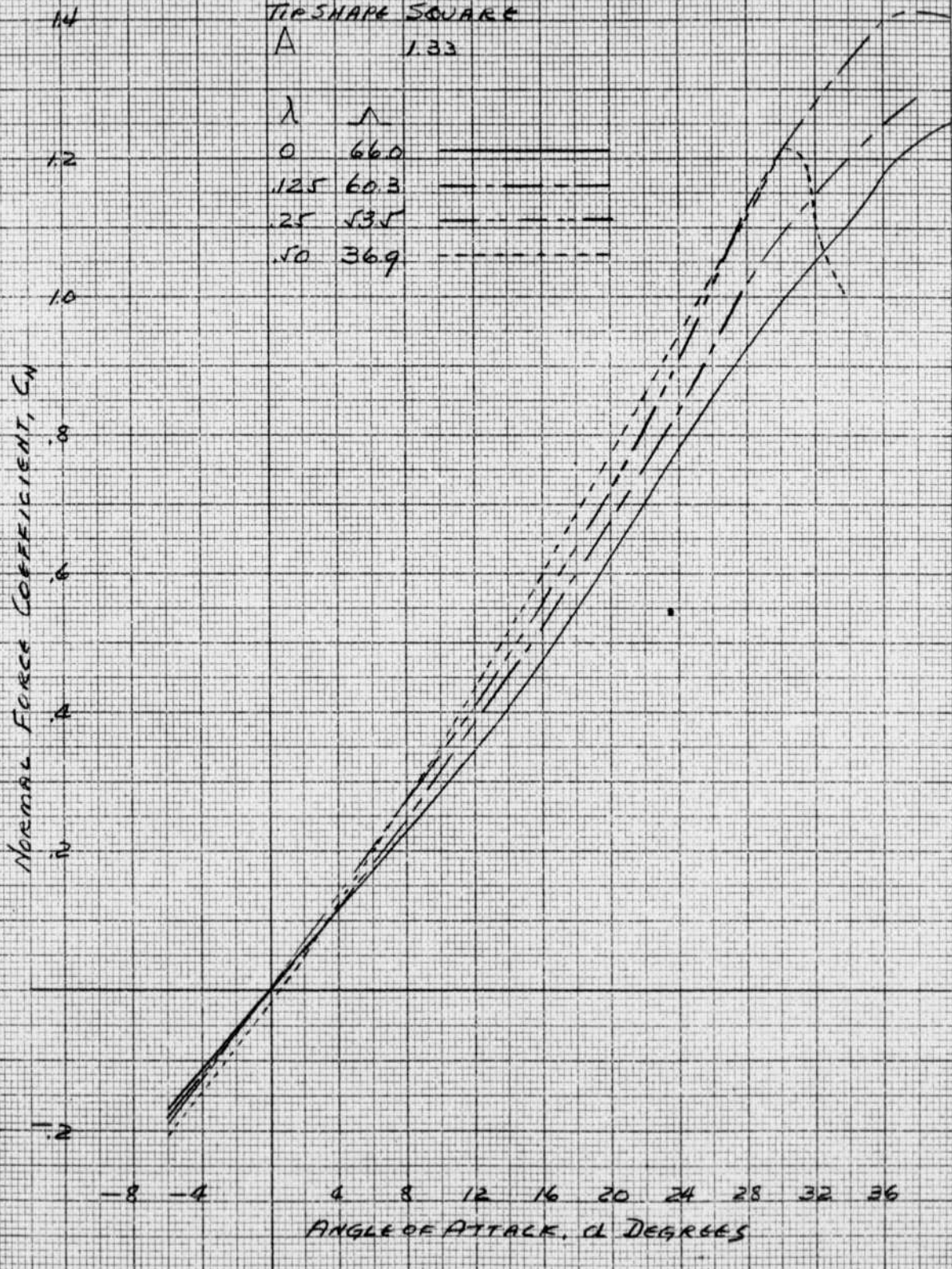


FIGURE 31 C

SECTION NACA 0012

TIP SHAPE SQUARE

A 1.33

λ	Δ	
0	66.0	—————
.125	60.3	-----
.25	53.5	-----
.50	36.9	-----

RESULTANT FORCE COEFFICIENT, C_R

16

14

12

10

8

6

4

2

-8

-4

4

8

12

16

20

24

28

32

36

ANGLE OF ATTACK, α DEGREES

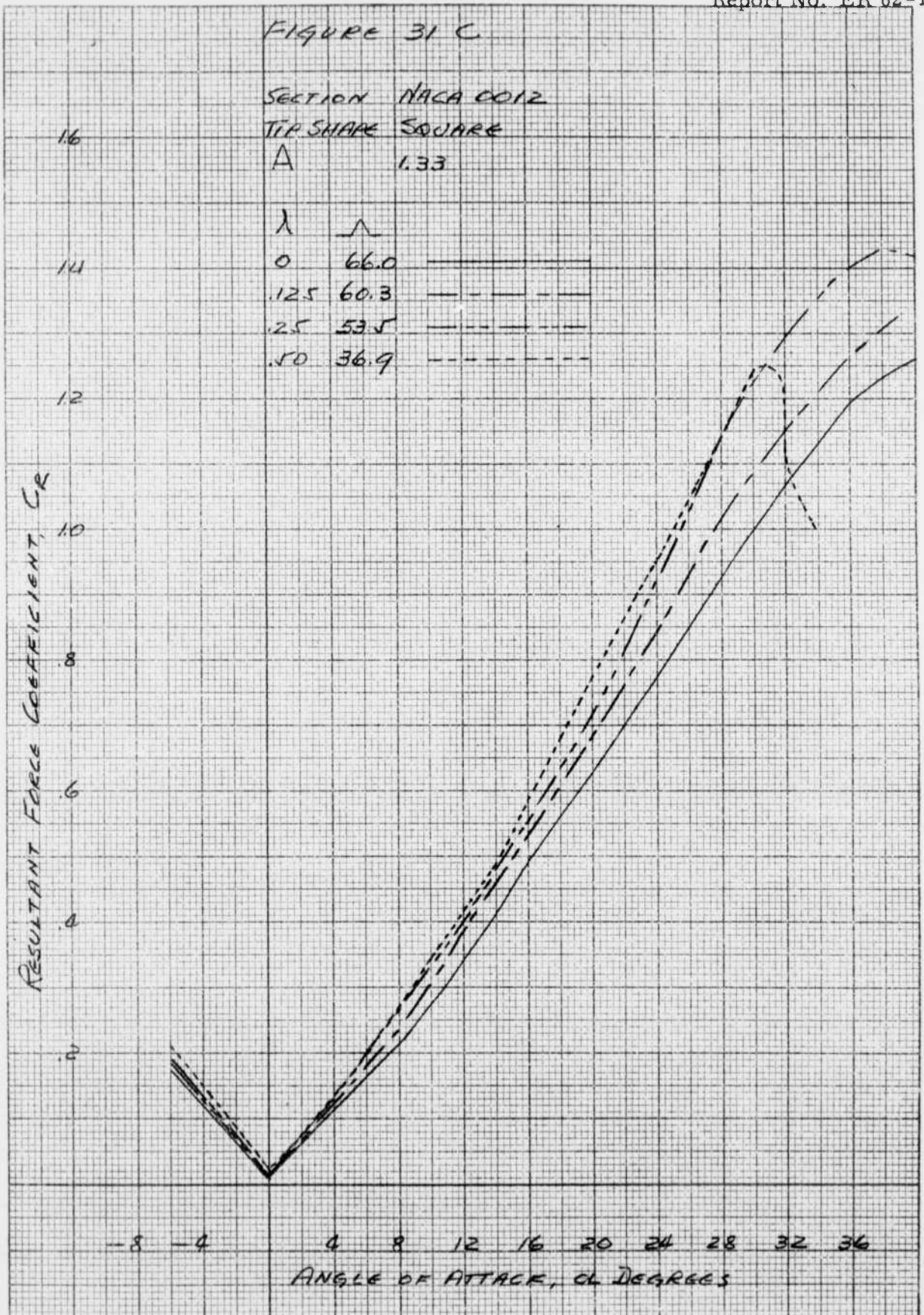


FIGURE 31.D

SECTION NACA 0012
TIP SHAPE SQUARE
A 1.33

λ	Λ	
0	66.0	—————
.125	60.2	-----
.25	53.5	-----
.50	36.9	-----

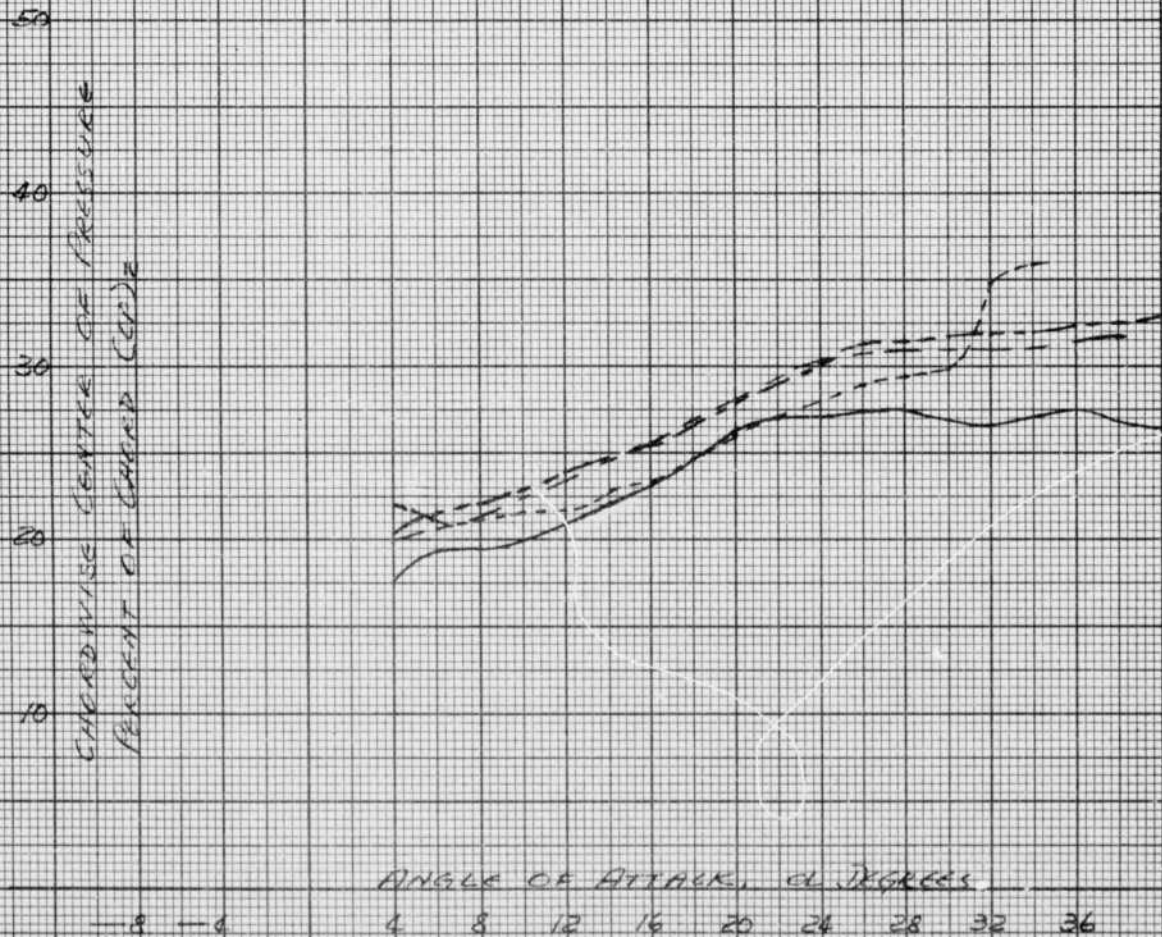


FIGURE 32

12

SECTION
TIP SHAPE
 λ

NACA 0012
SQUARE
0

1.0

A	Δ
1.00	71.6
1.33	66.0
2.00	56.3

.8

.6

.4

.2

0

-.2

-.4

-.6

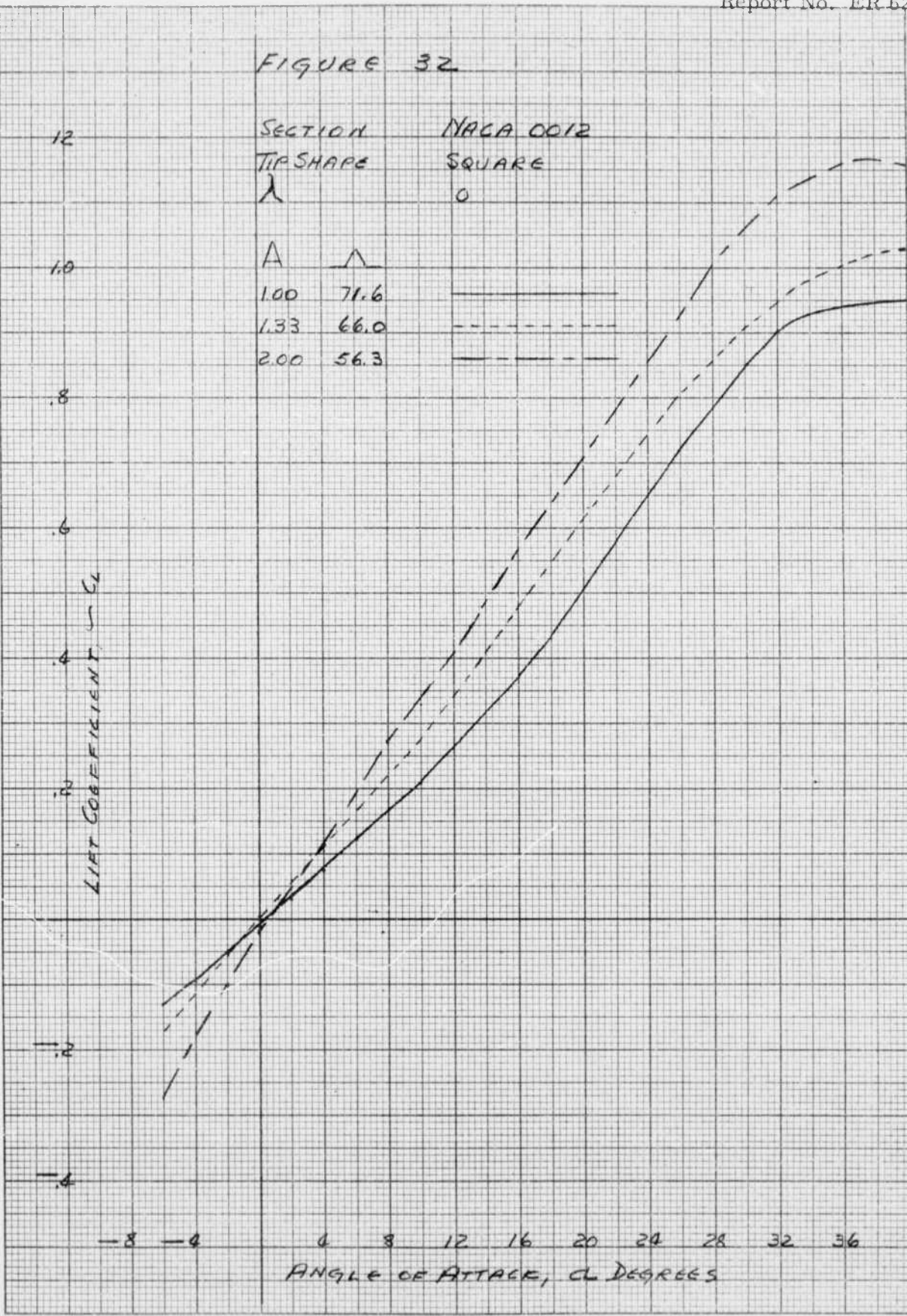
-.8

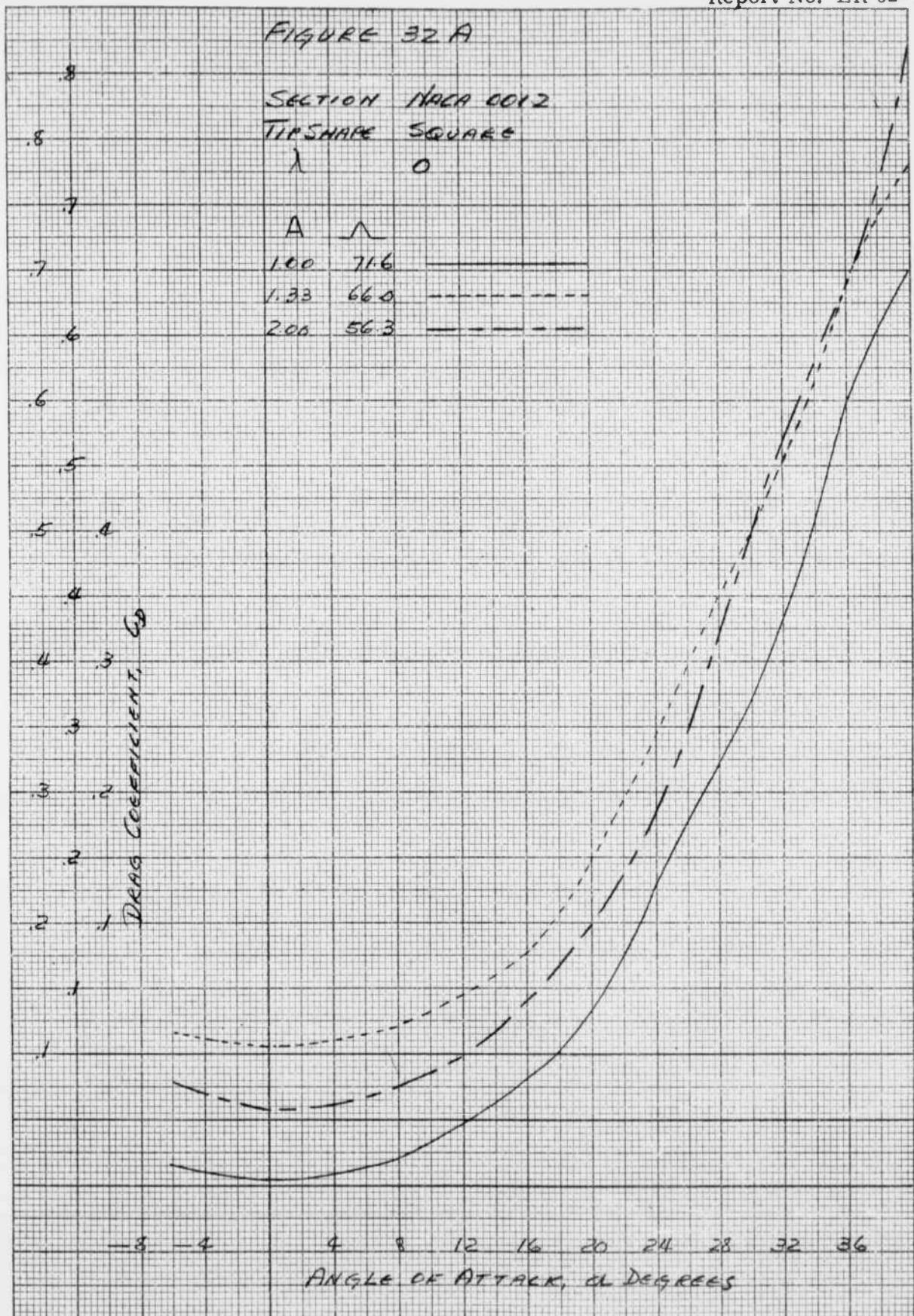
LIFT COEFFICIENT, C_L

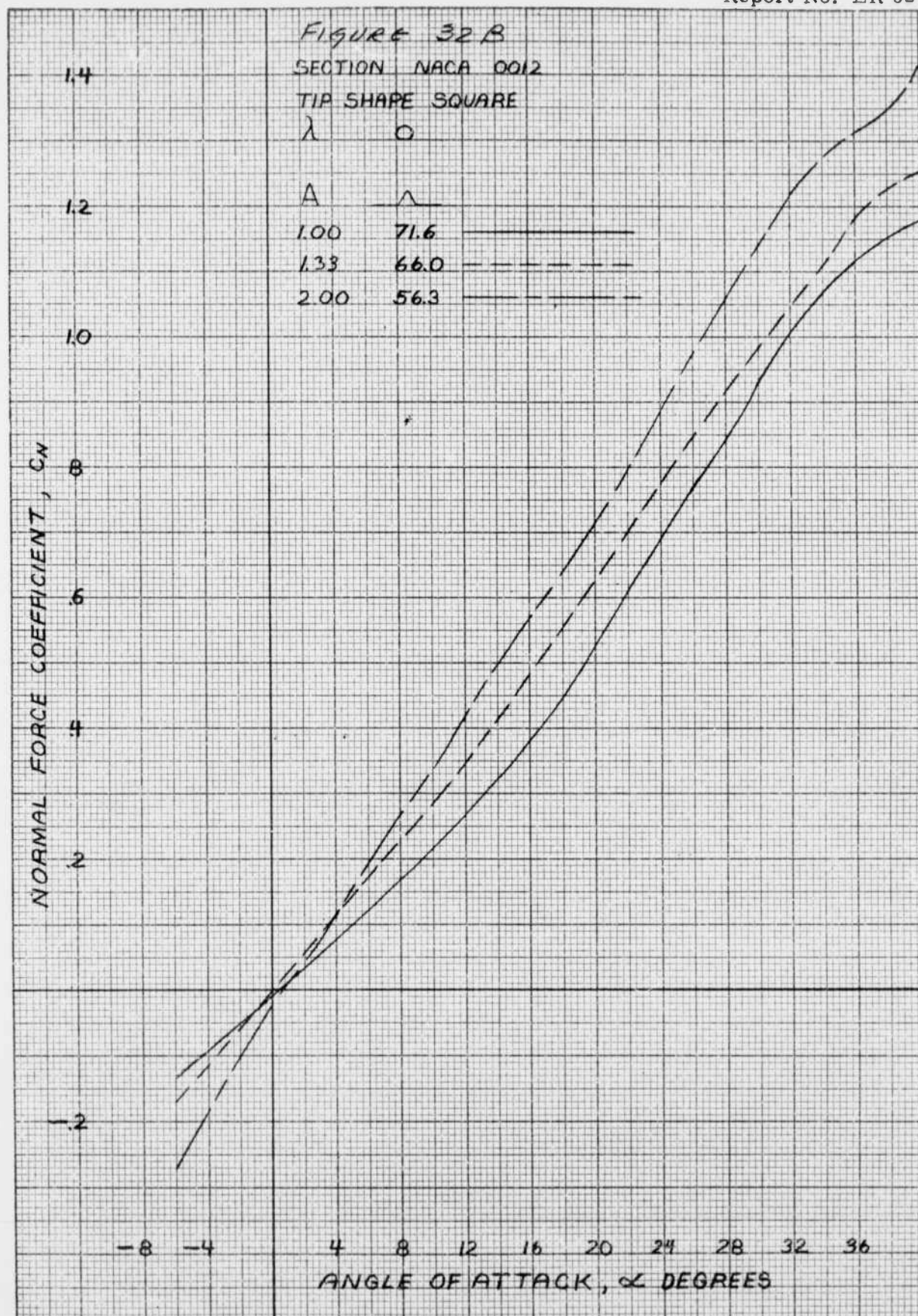
-8 -4

4 8 12 16 20 24 28 32 36

ANGLE OF ATTACK, α DEGREES







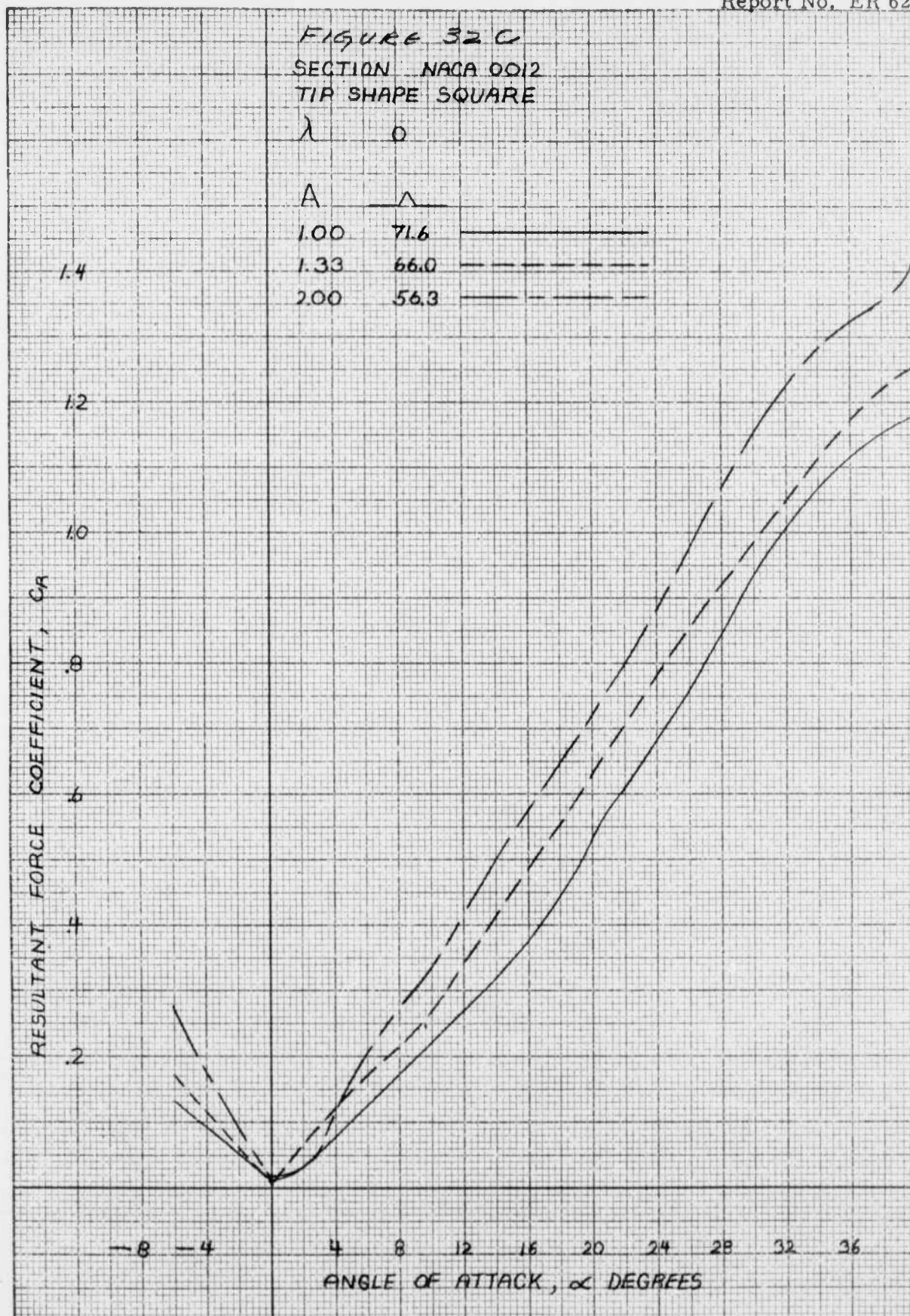


FIGURE 32D

SECTION NACA 0012

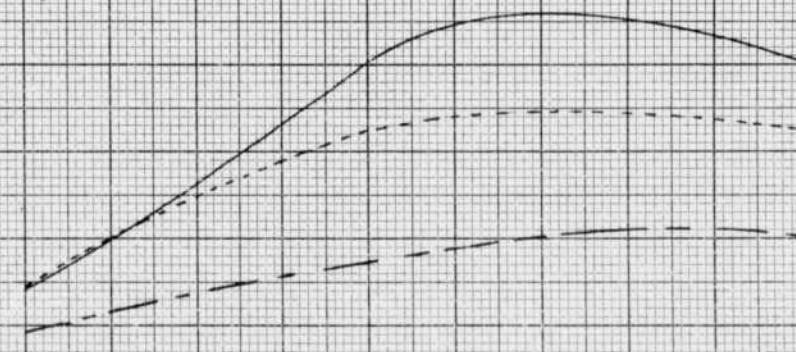
TIP SHAPE SQUARE

λ 0

A	Δ	
1.00	71.6	—————
1.33	66.0	-----
2.00	56.3	-----

CHORDWISE CENTER OF PRESSURE
PERCENT OF CHORD, $(C_p)_2$

40
30
20
10



-8 -4

4 8 12 16 20 24 28 32 36

ANGLE OF ATTACK, α DEGREES

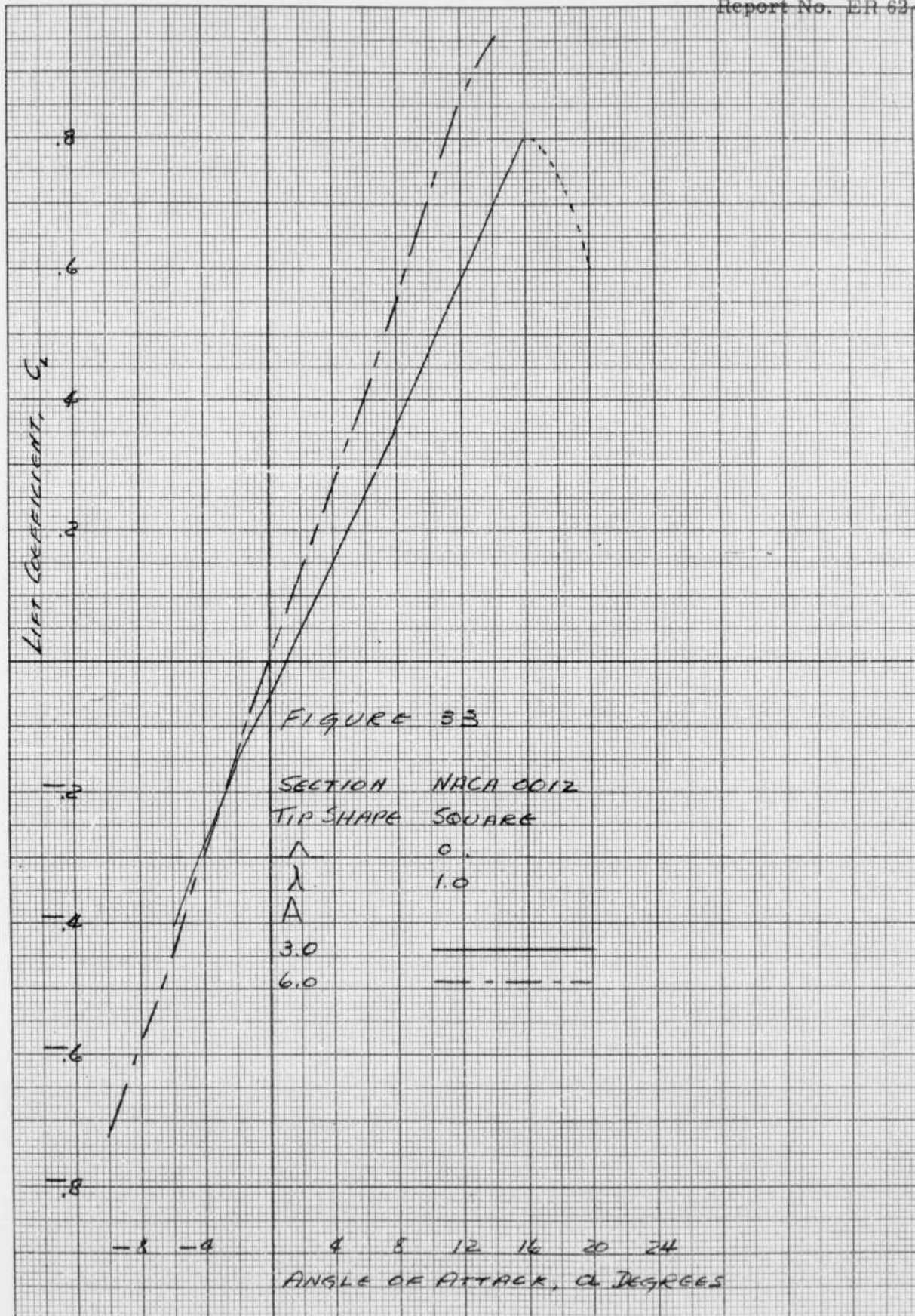
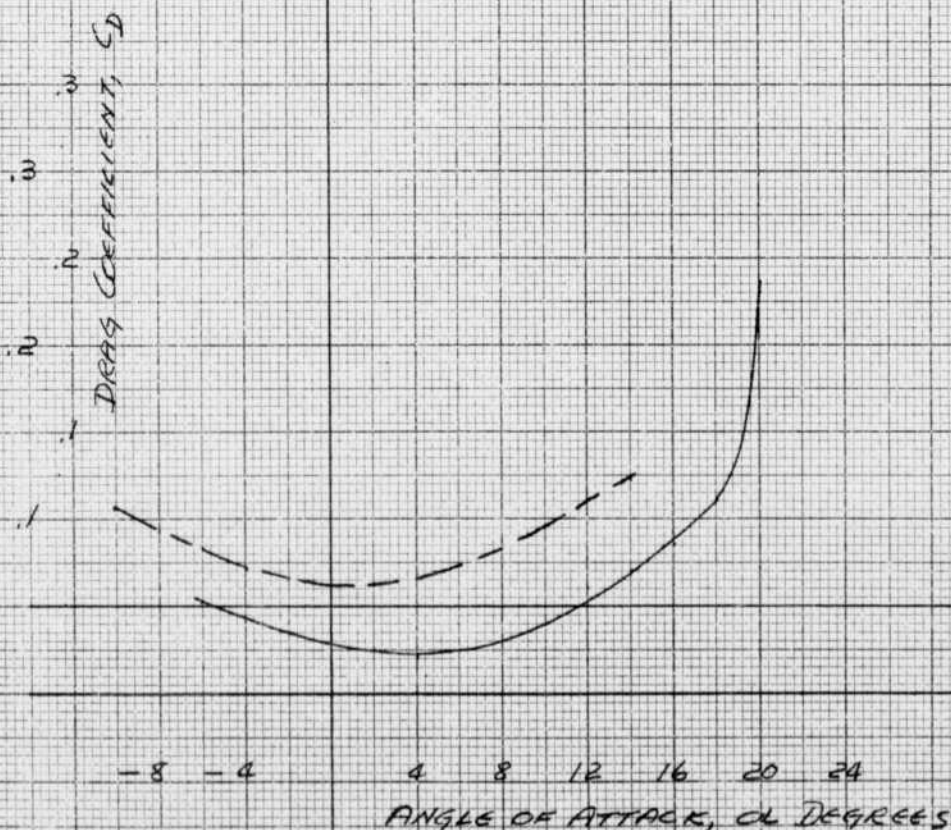


FIGURE 33A

SECTION	NACA 0012
TIP SHAPE	SQUARE
Λ	0°
λ	1.0
A	
3.0	—————
6.0	- - - - -



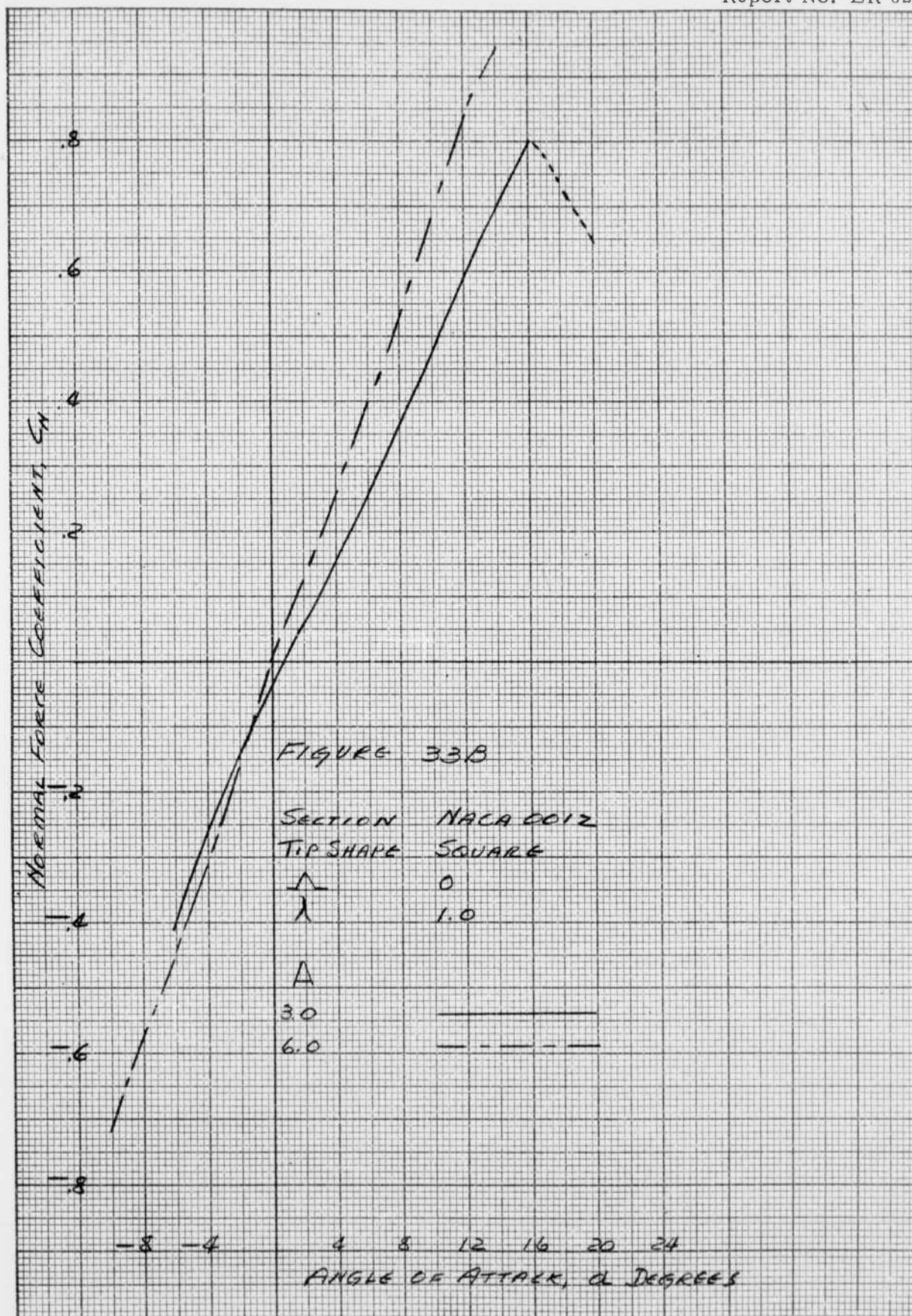


FIGURE 33C

SECTION NACA 0012
TIP SHAPE SQUARE

λ 0
 λ 1.0

A
3.0 —————
6.0 - - - - -

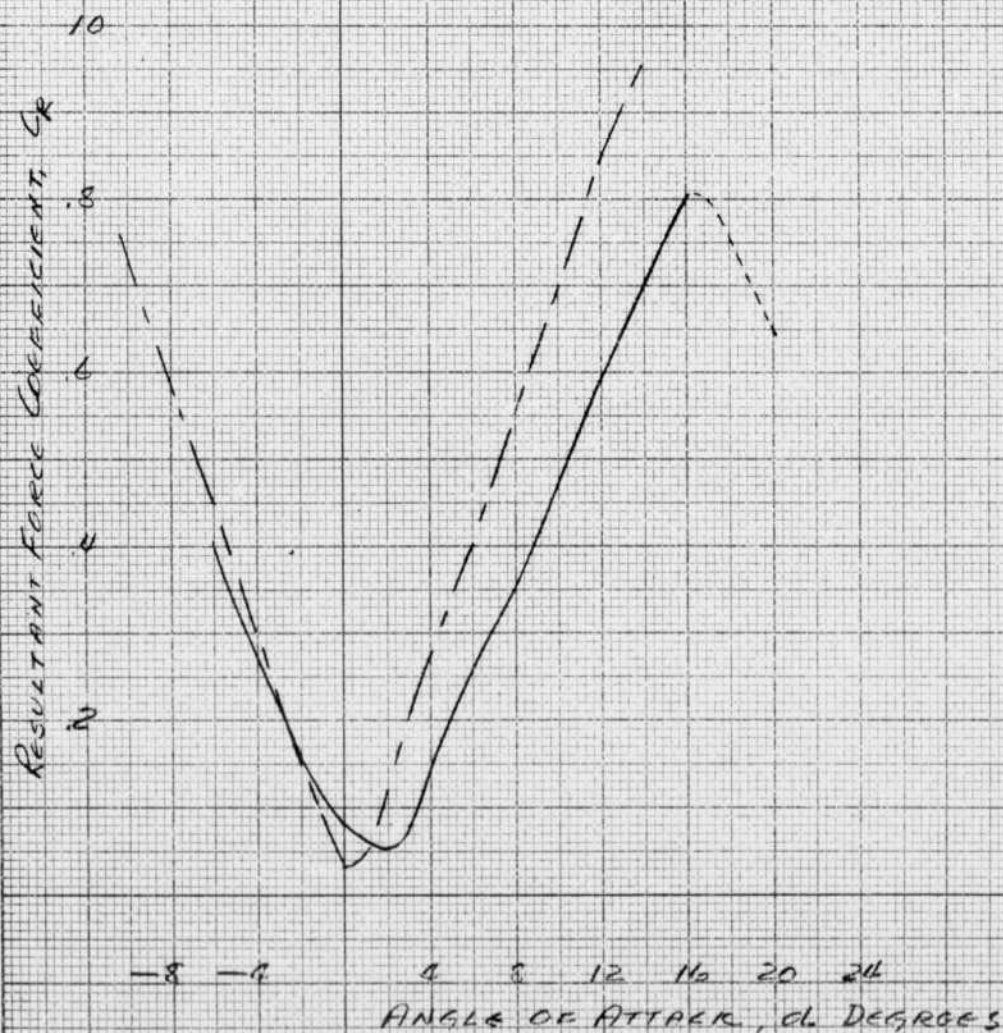


FIGURE 33D

SECTION NACA 0012

TIP SHAPE SQUARE

 Λ 0° λ 1.0

A

3.0

6.0

CHORDWISE CENTER OF PRESSURE
PERCENT OF CHORD, (C_{CP})_x

-8 -4

4 8 12 16 20 24

ANGLE OF ATTACK, CL DEGREES

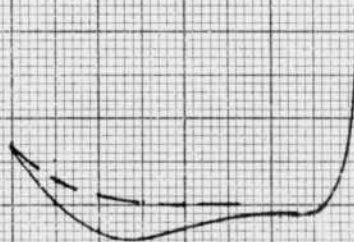


FIGURE 34

SECTION NACA 0012

TIP SHAPE SQUARE

λ 5

Δ Δ

1.33 36.9

3.00 6.34

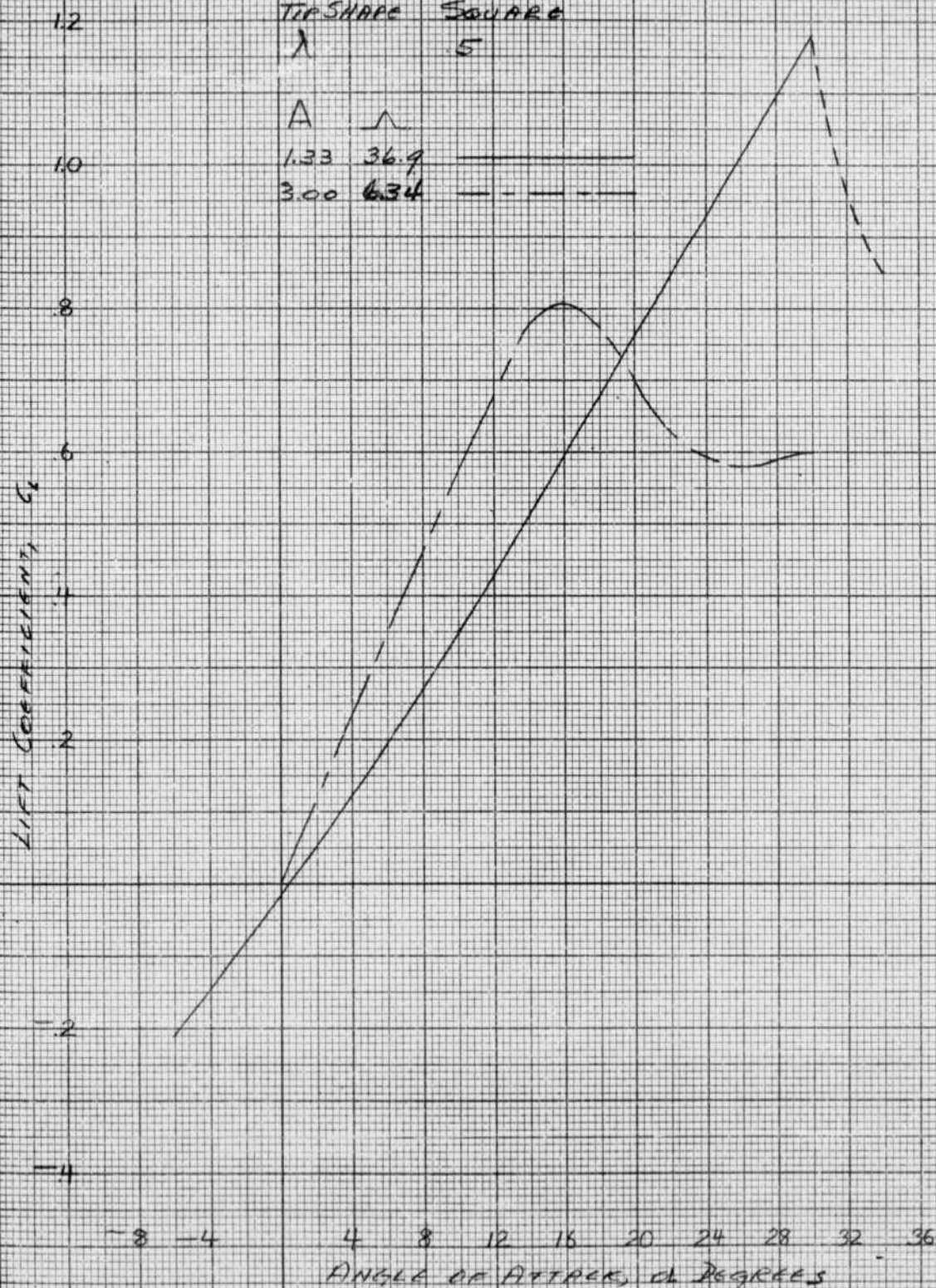


FIGURE 34 A

SECTION NACA 0012

TIP SHAPE SQUARE

 λ .5A λ

1.33 36.9

300 634

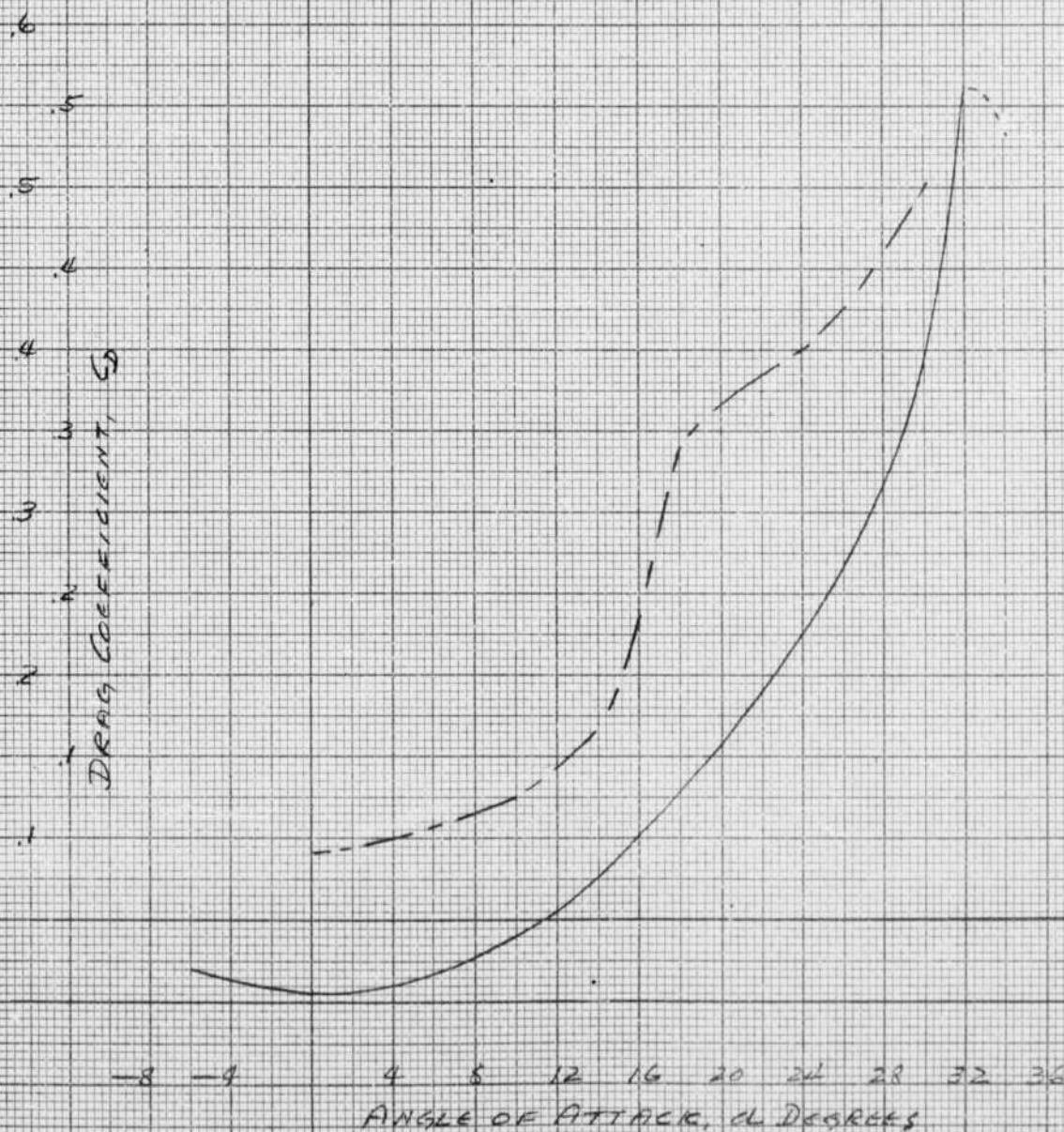


FIGURE 34B

SECTION NACA 0012

WING SHAPE SQUARE

1 .5

1.33 1.5

300 6.54

NORMAL FORCE COEFFICIENT, C_N

-8 -4 0 4 8 12 16 20 24 28 32 36

ANGLE OF ATTACK, α , DEGREES

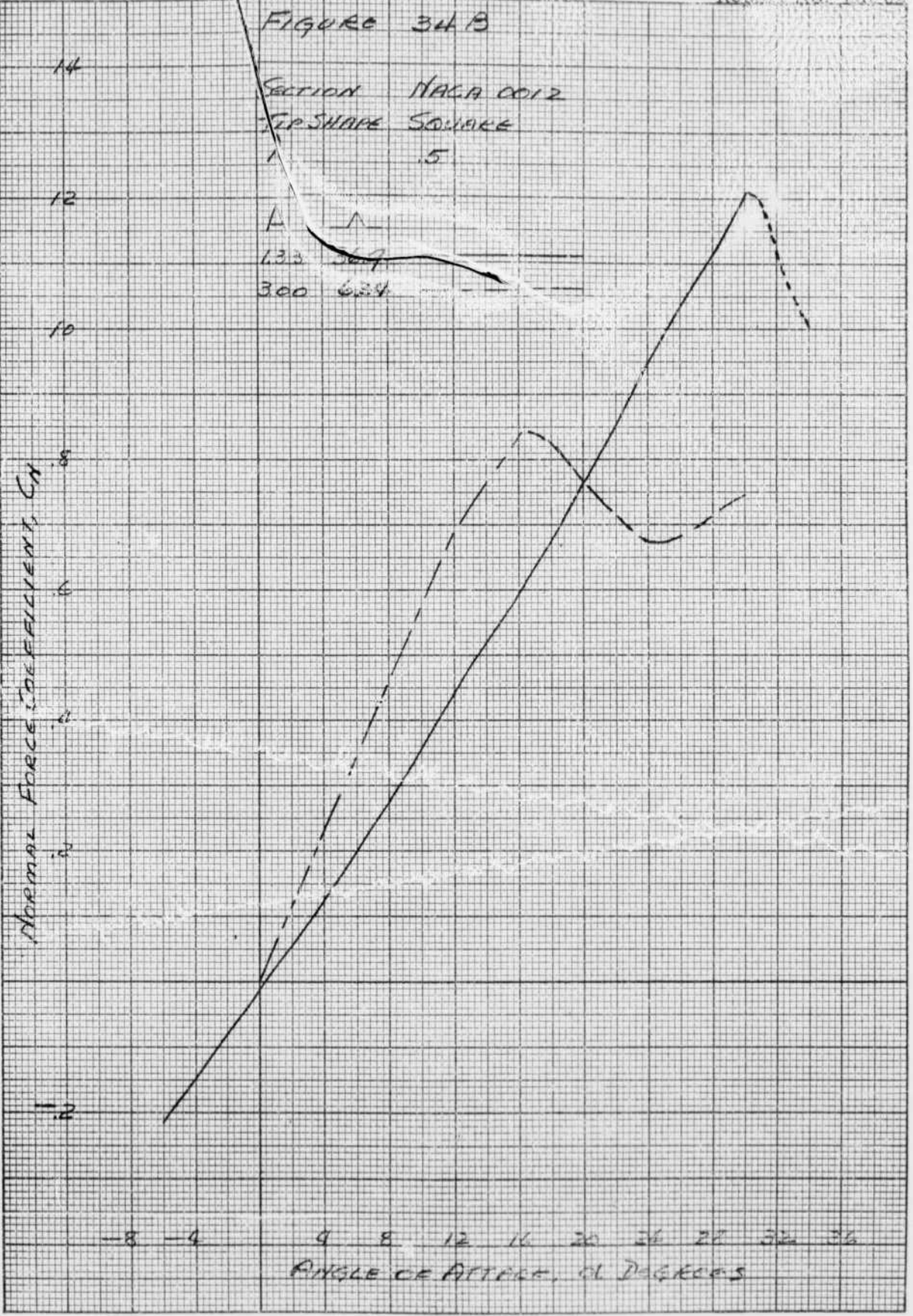


FIGURE 34C

SECTION NACA 0012

TIP SHAPE SQUARE

λ .5

A Δ

1.33 36.9 —————

3.00 6.34 - - - - -

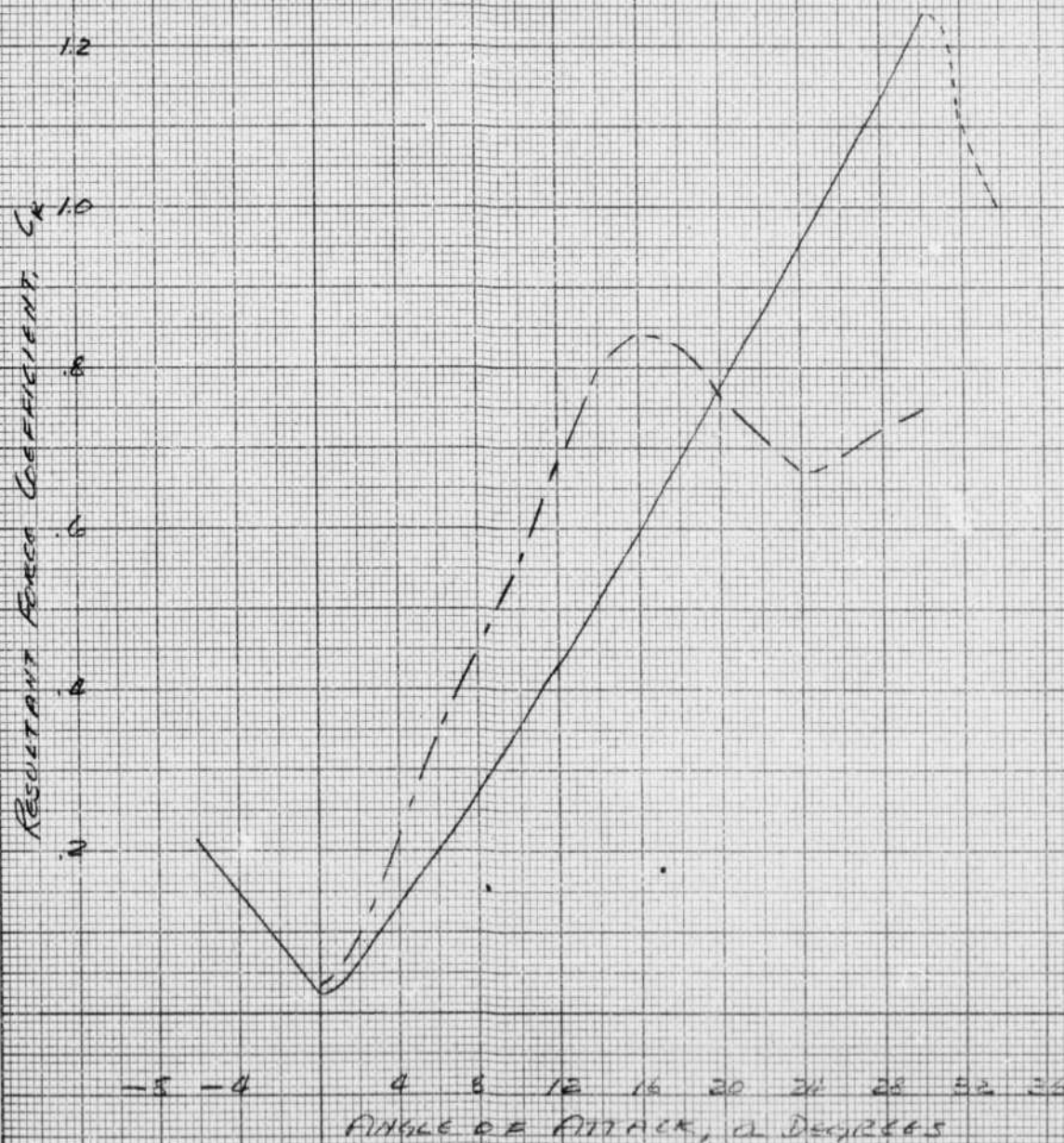


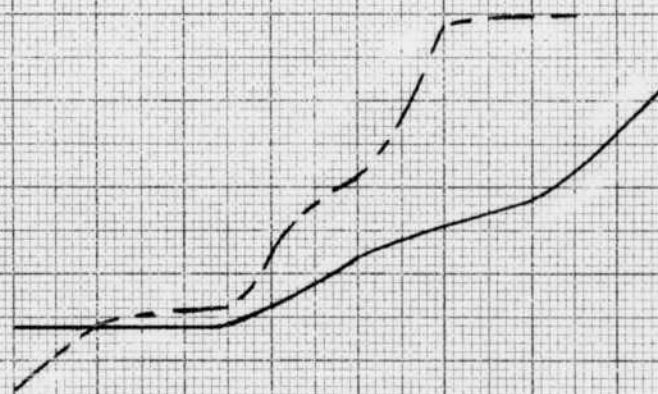
FIGURE 34D

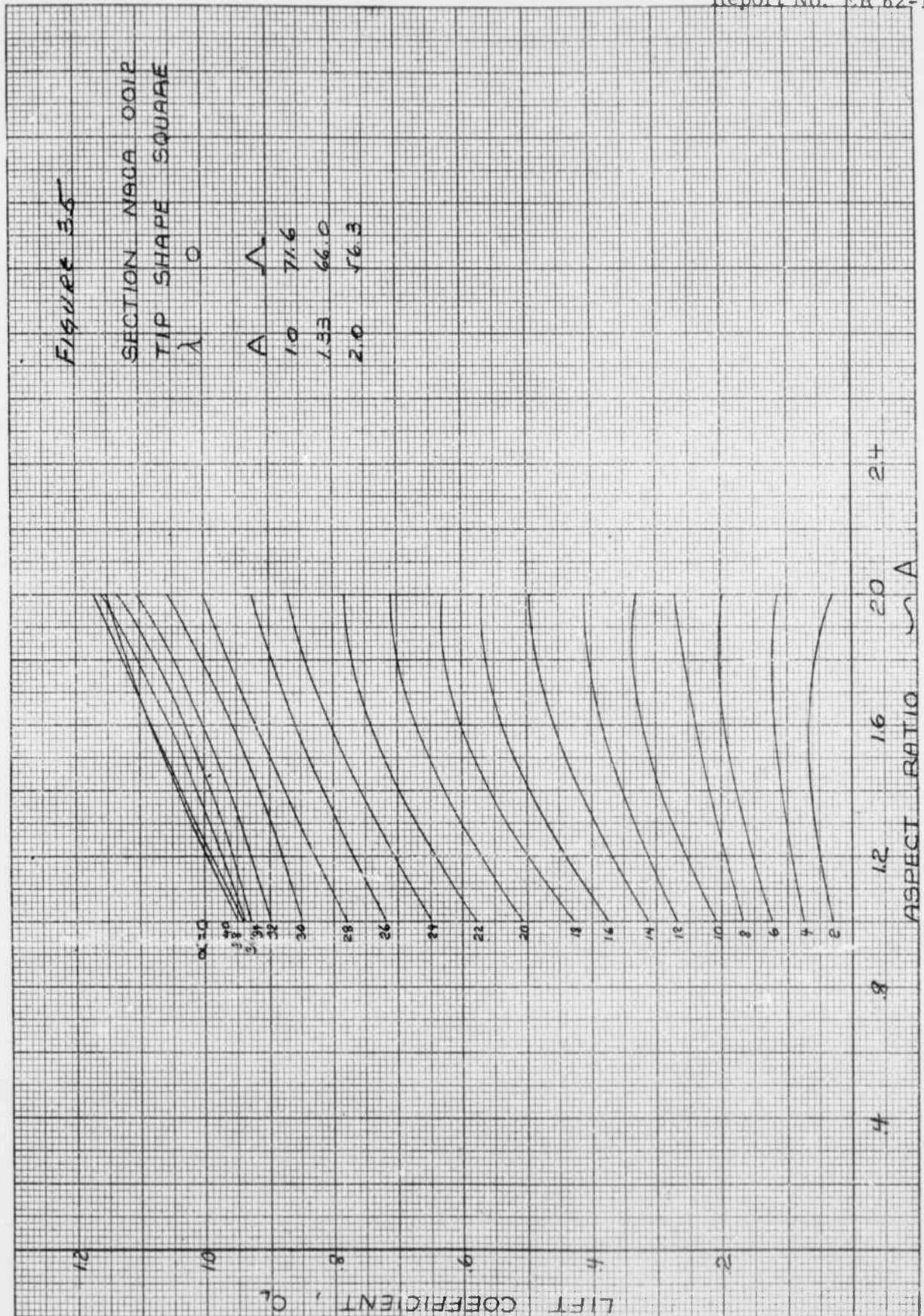
SECTION NACA 0012
TIP SHAPE SQUARE
 λ 5

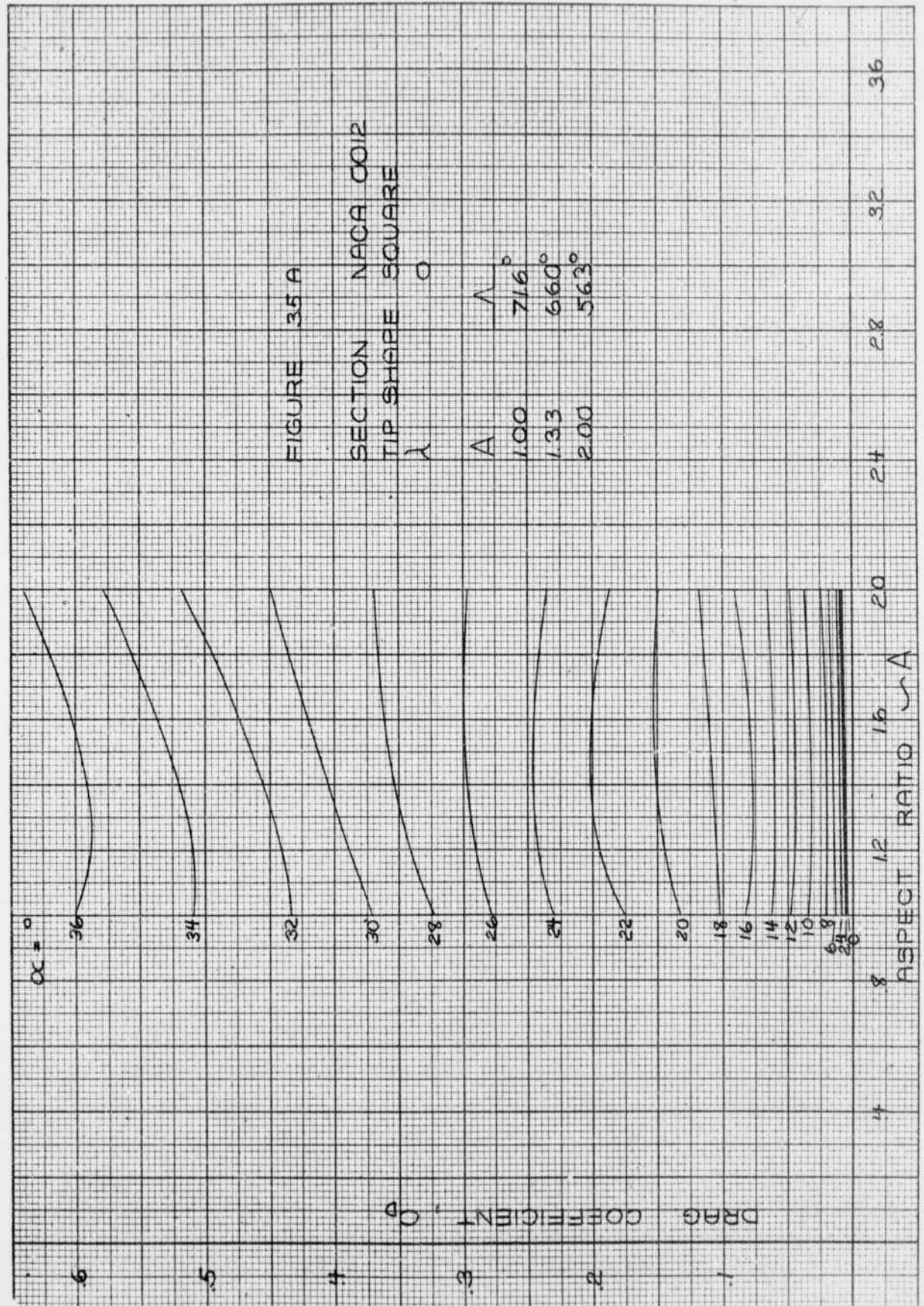
A Λ
133 36.9 ————
3.00 634 - - - - -

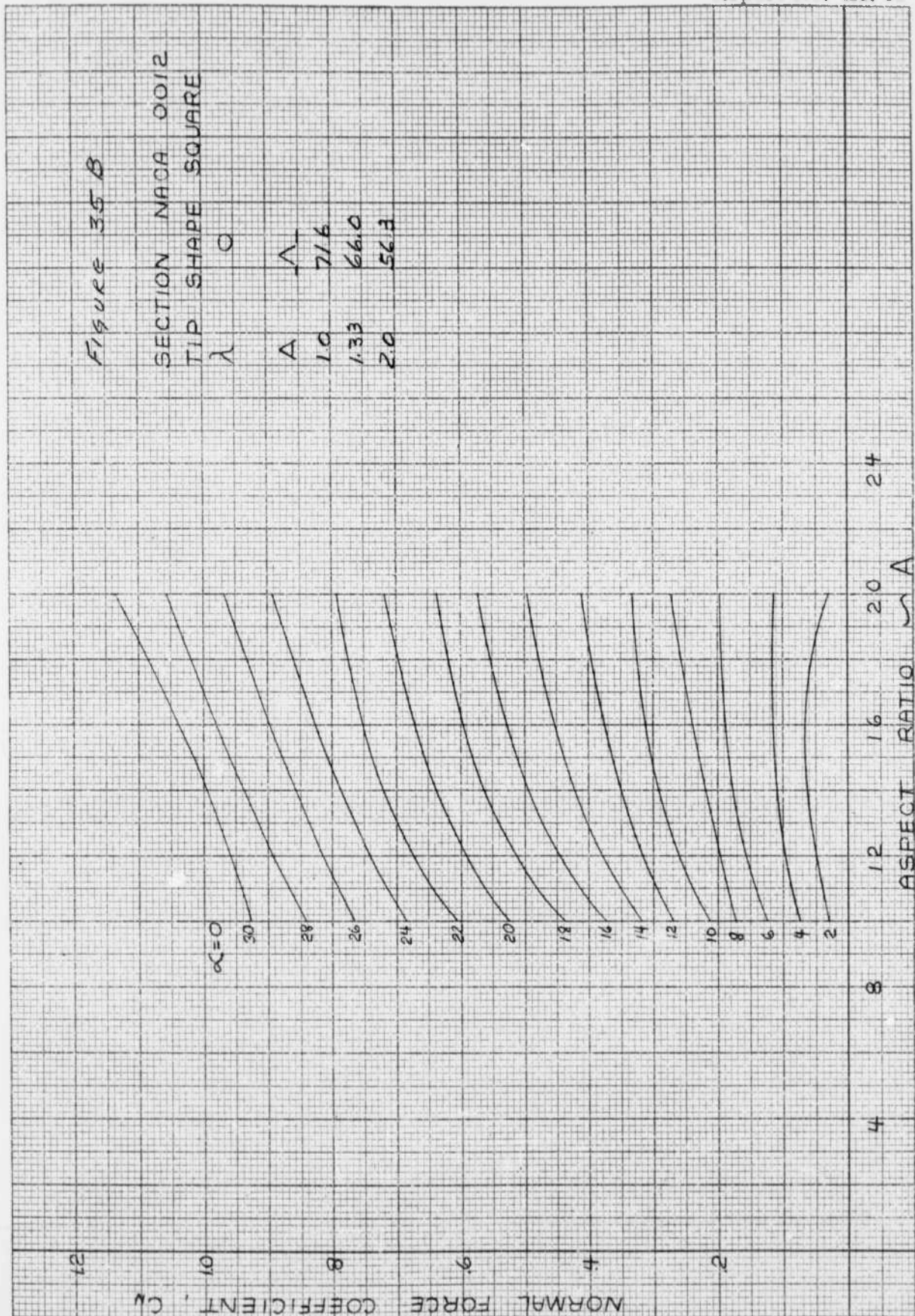
40
30
20
10
CIRCULAR CENTER OF PRESSURE
PERCENT OF CHORD (C.P.)

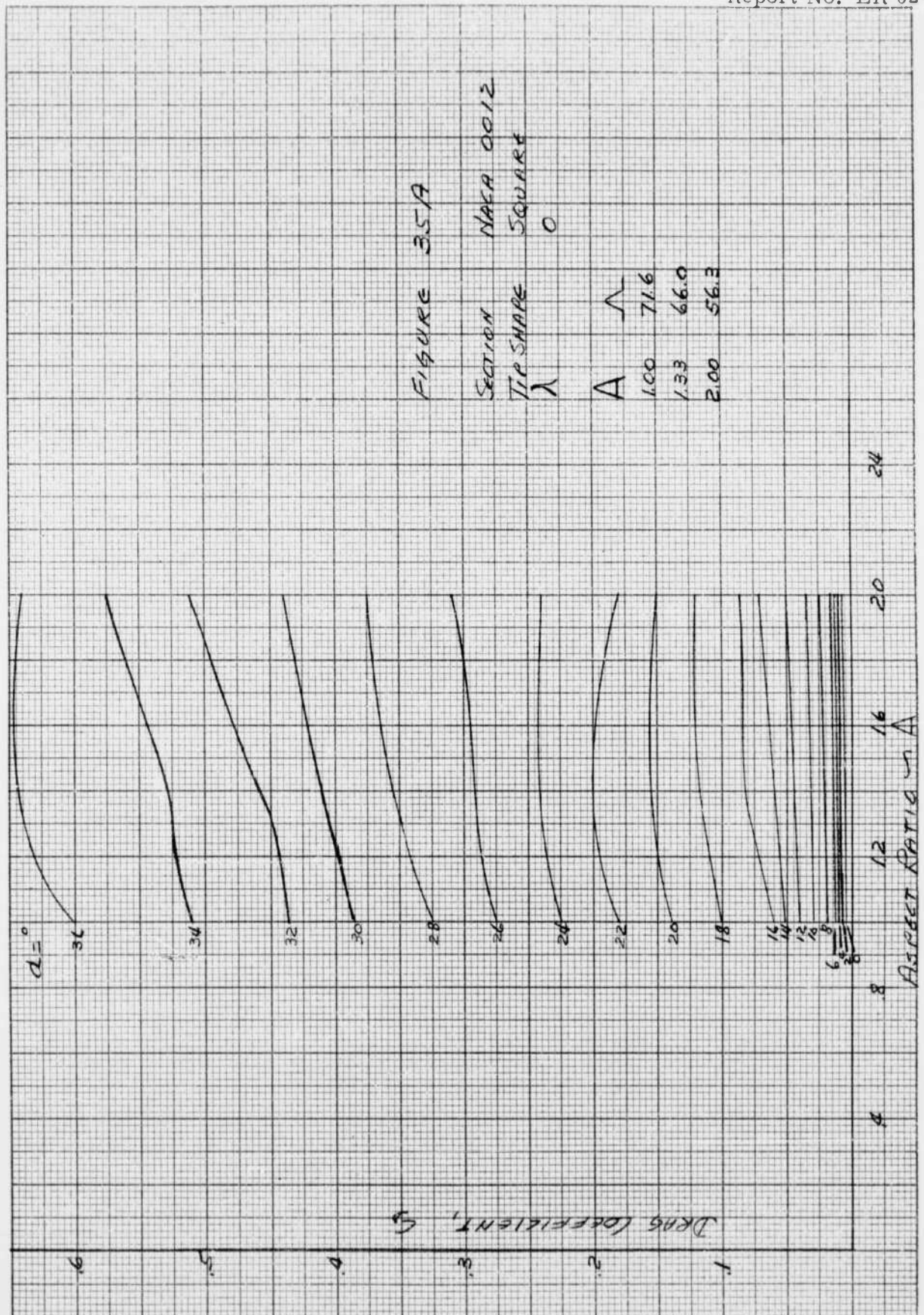
-8 -4 4 8 12 16 20 24 28 32 36
ANGLE OF ATTACK, α DEGREES

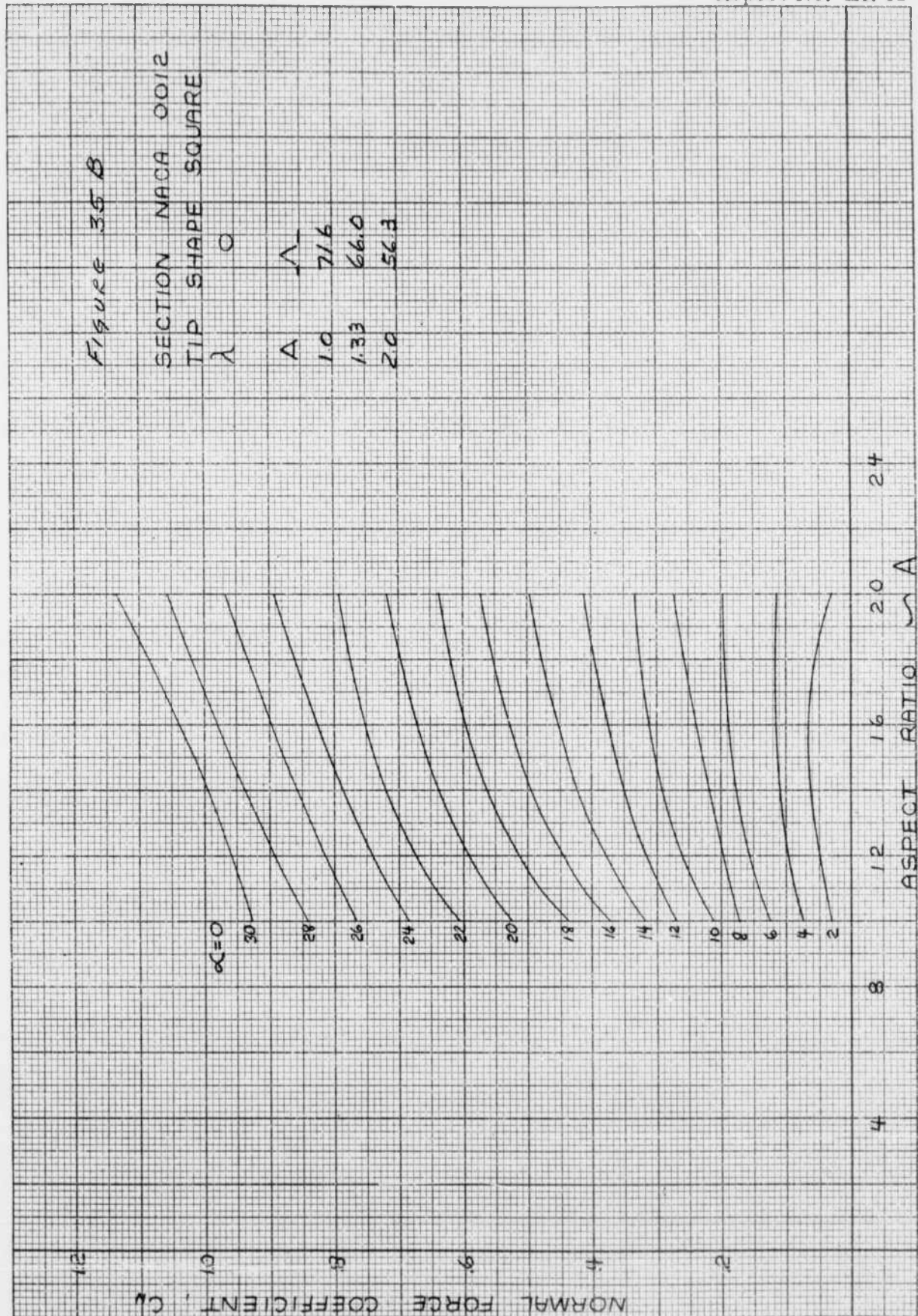


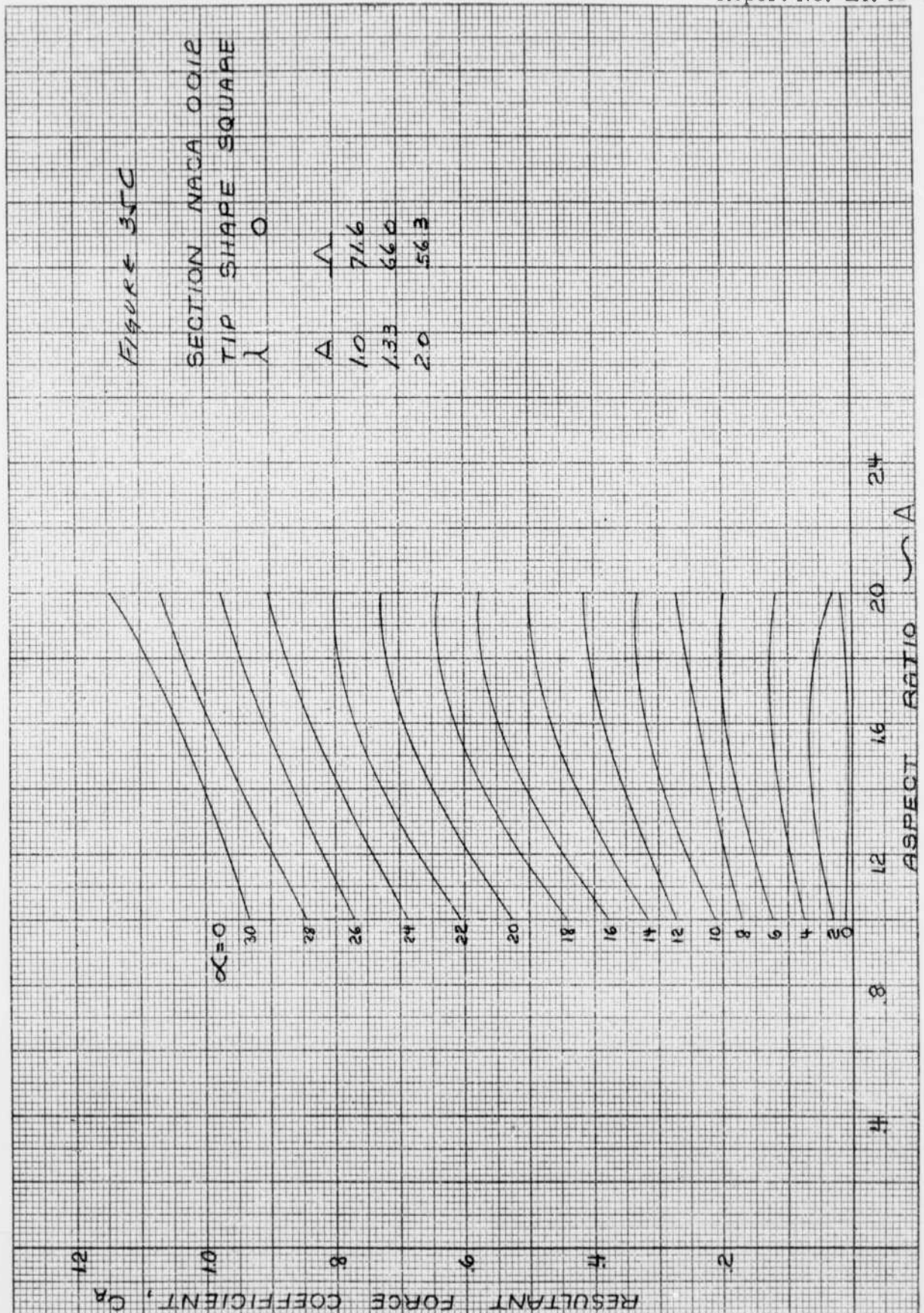


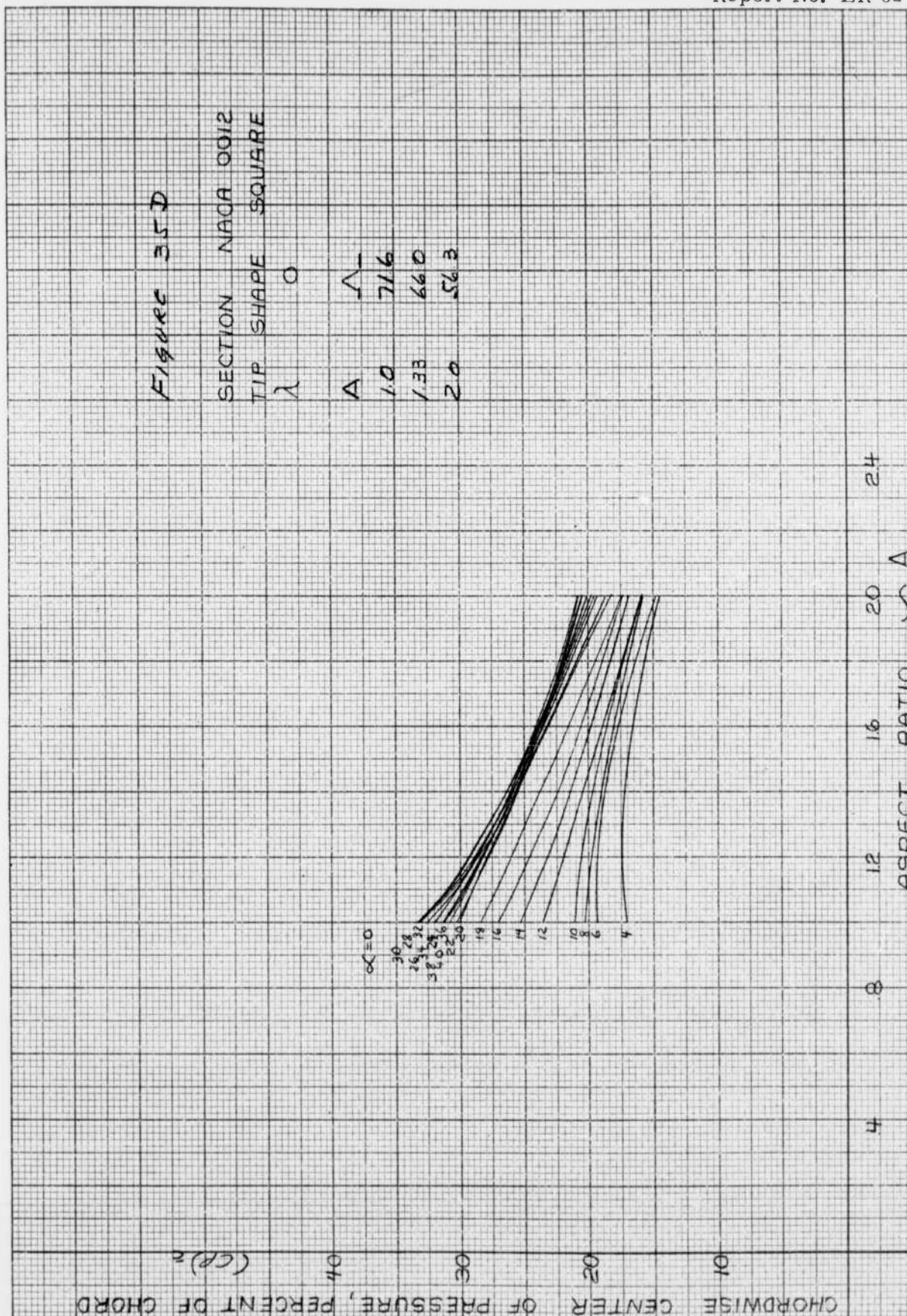


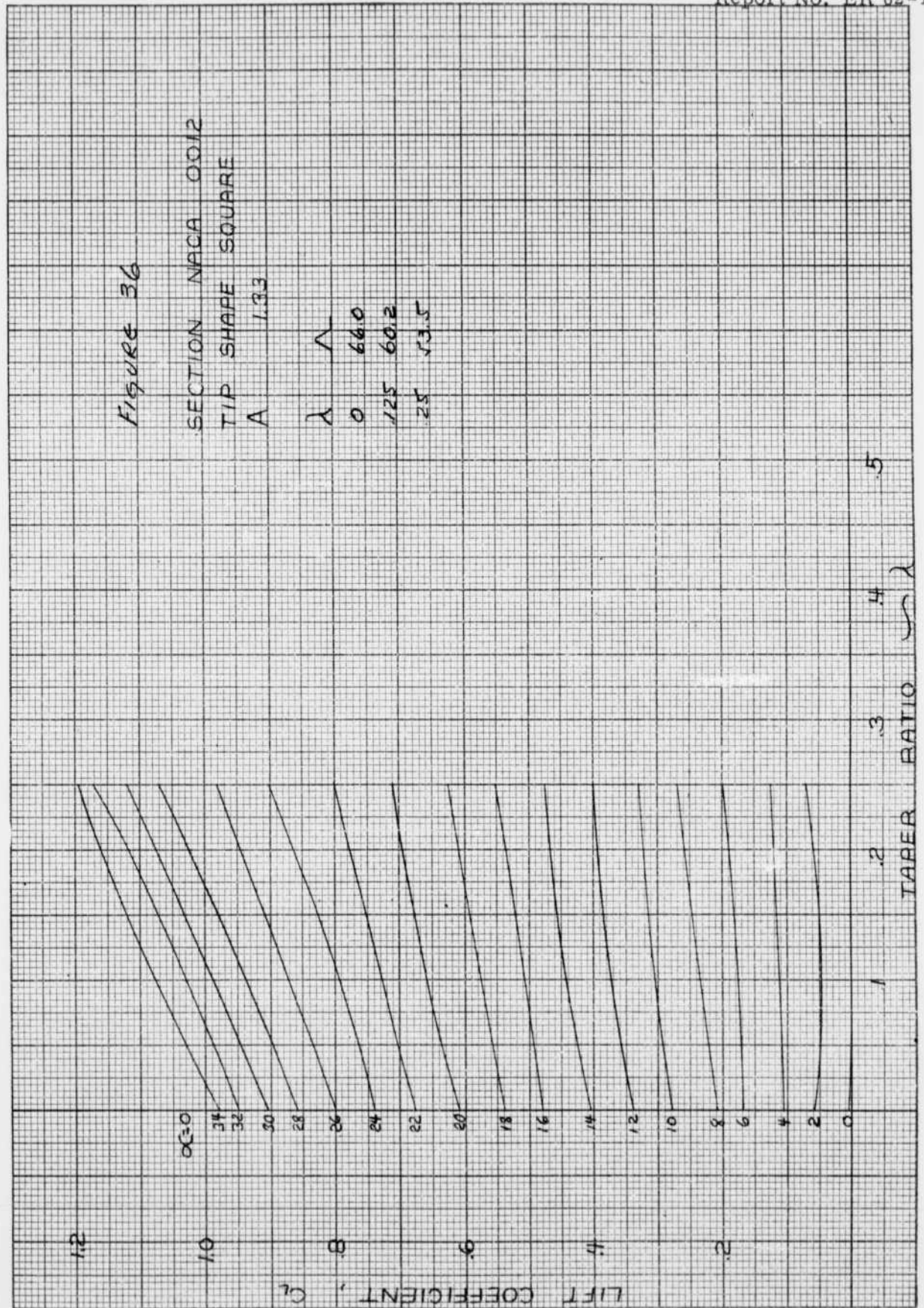


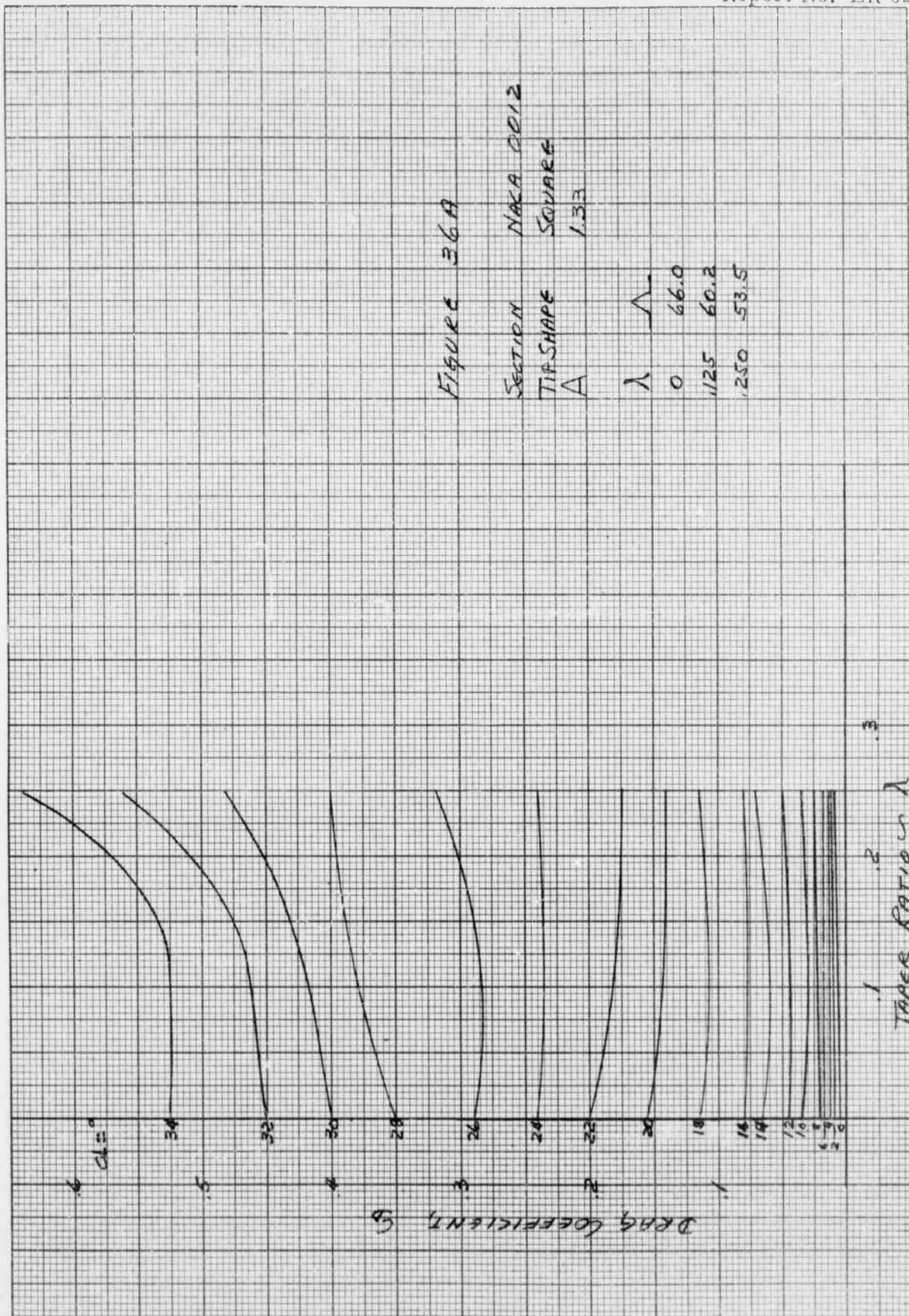


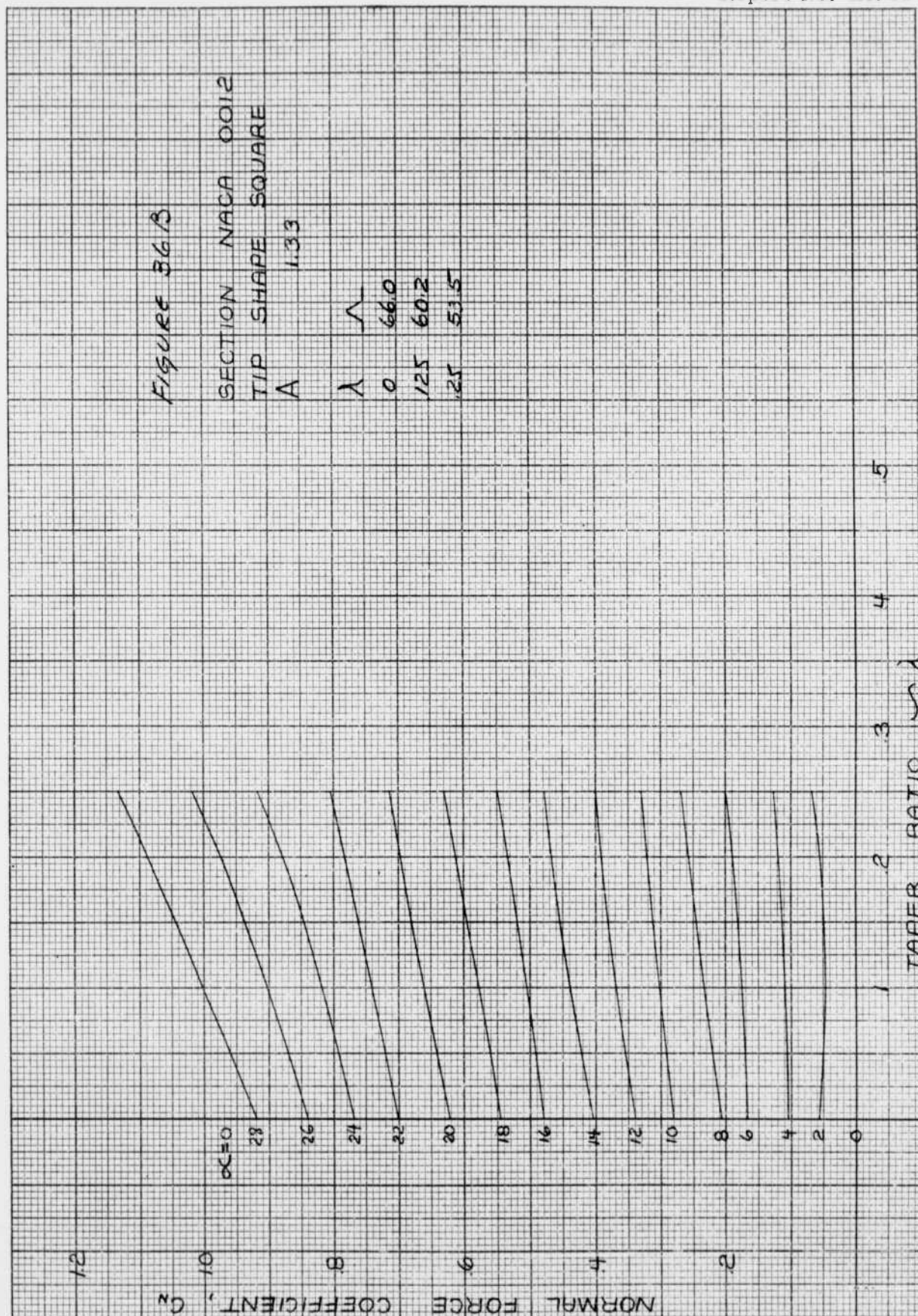


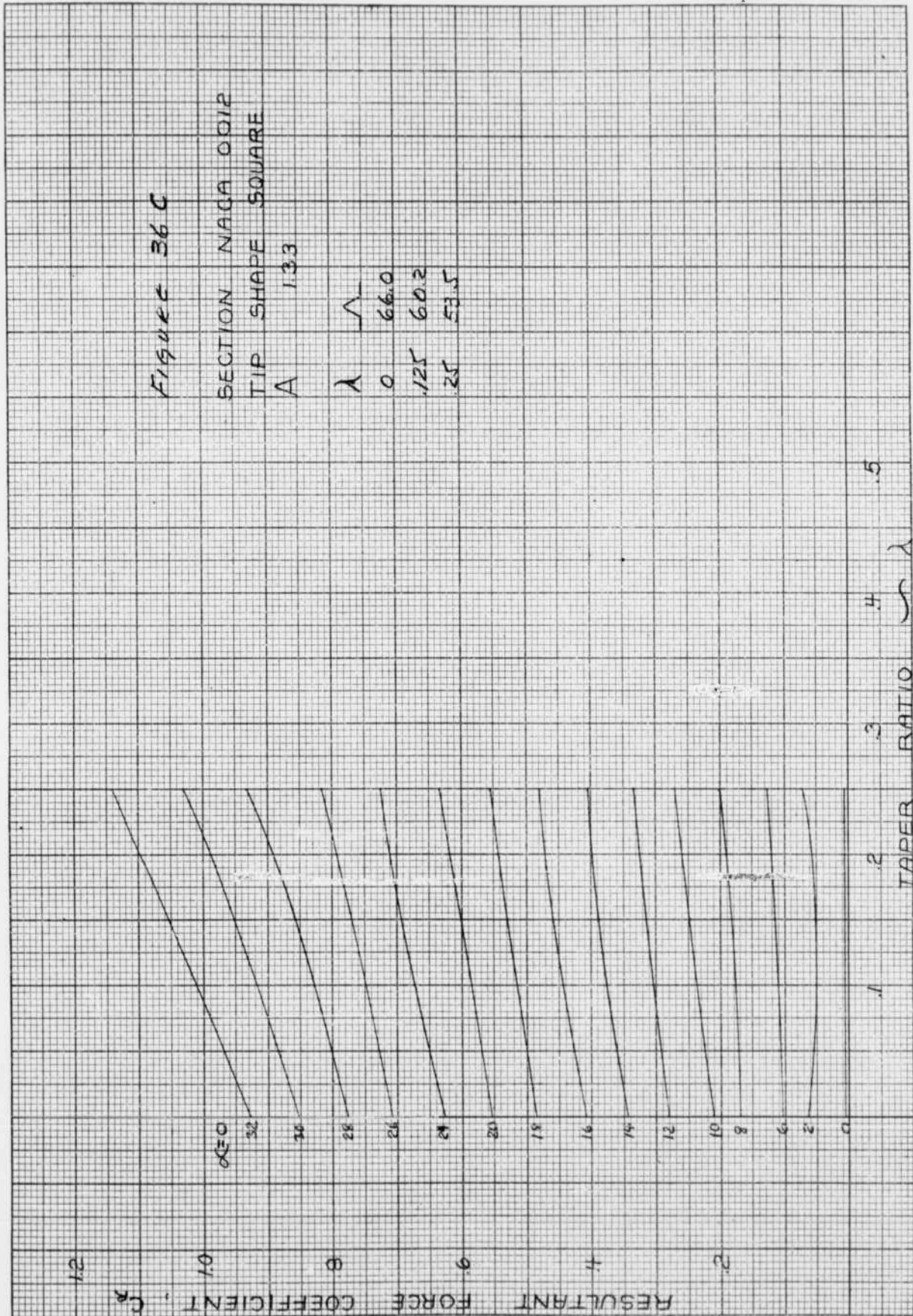












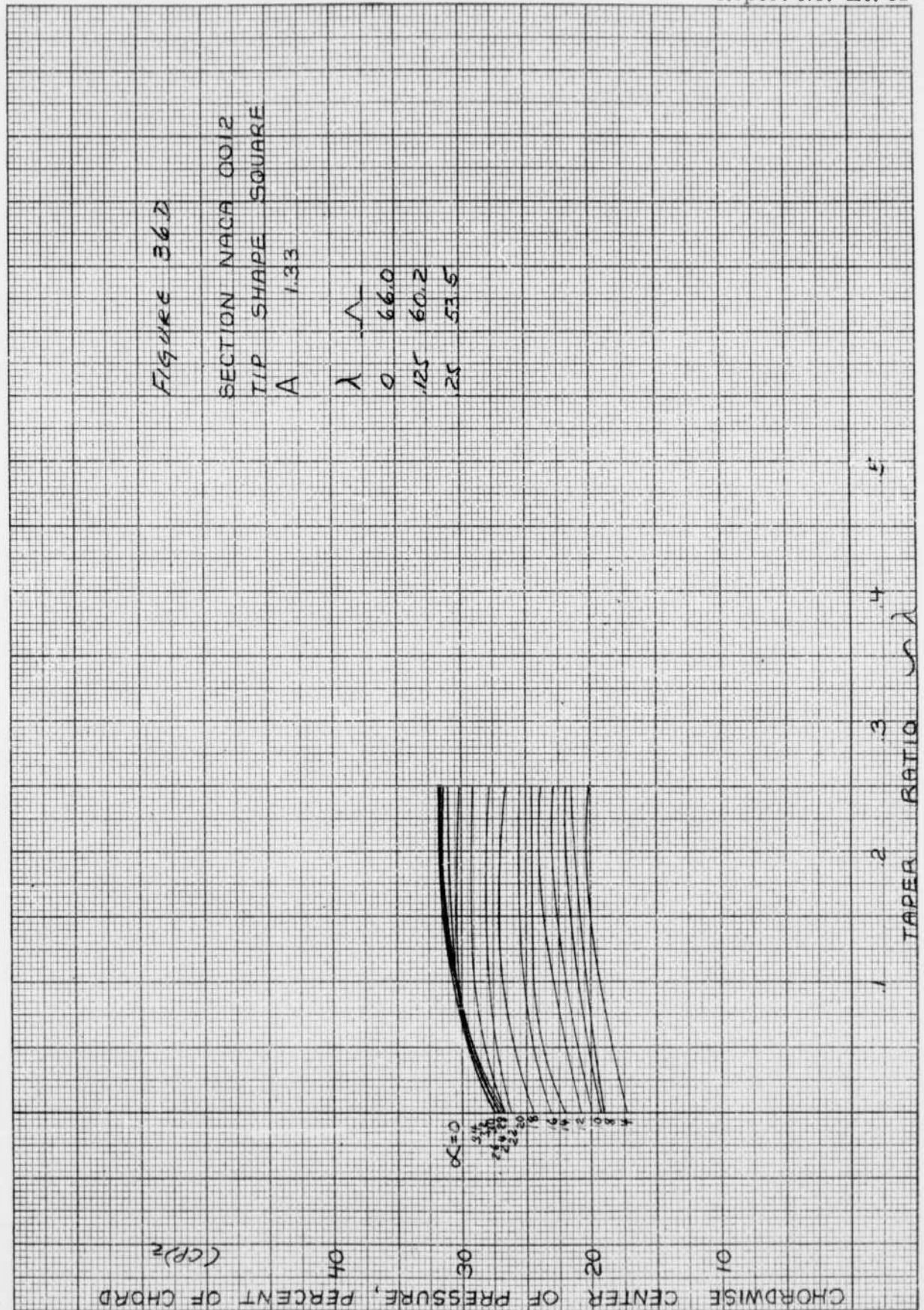


FIGURE 37

SECTION NACA0012
TIP SHAPE FAIRED

λ 0'
 λ 10

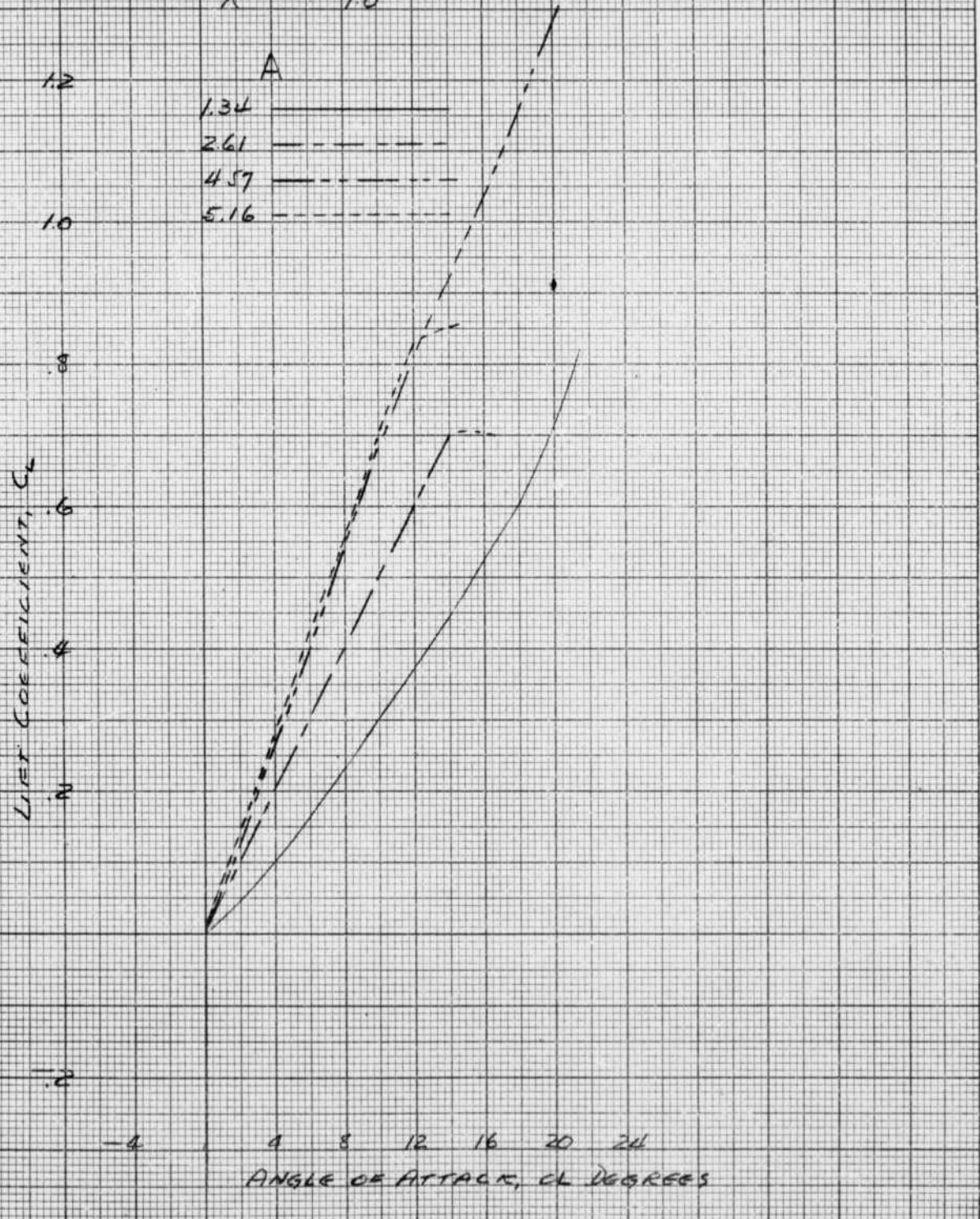


FIGURE 37A

SECTION NACA 0012
TIP SHAPE FAIRED

Λ 0°
 λ 10

A
1.34 —————
2.61 ————
4.57 ————
5.16 ————

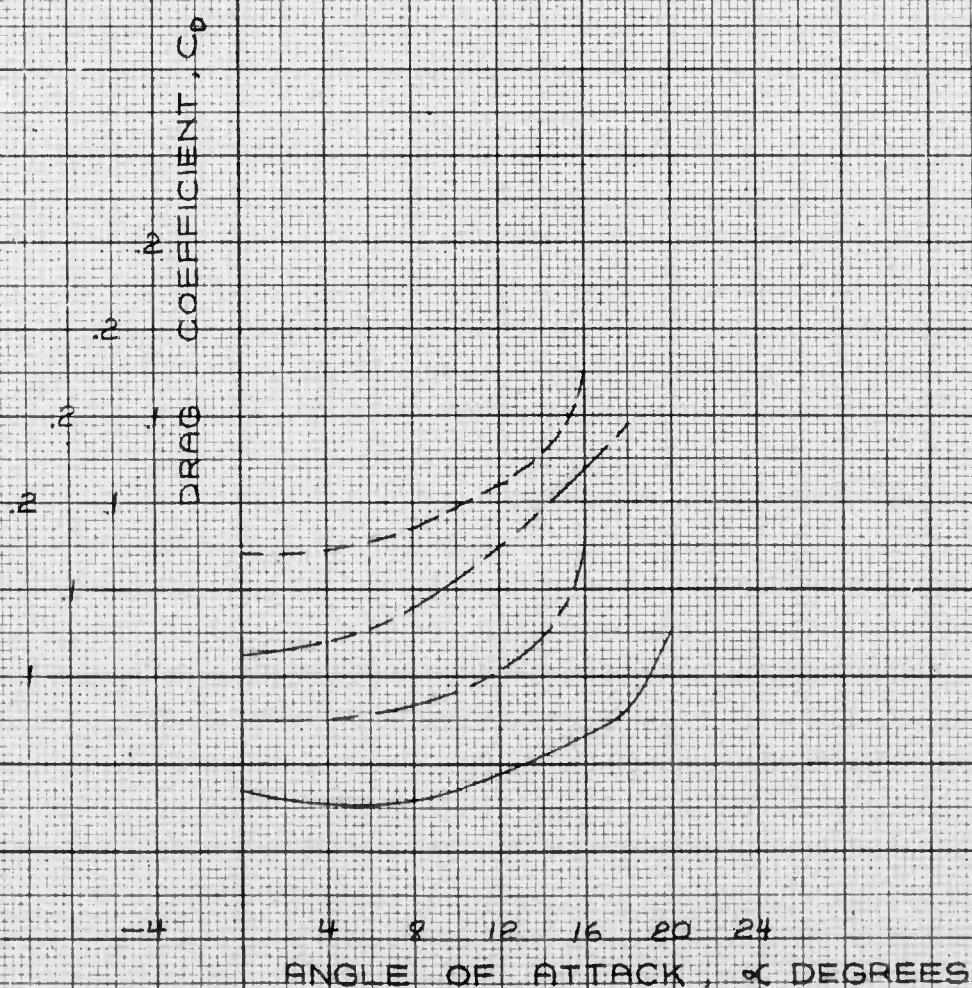


FIGURE 37B

SECTION NACA 0012
TIP SHAPE FAIRED

Λ 0°
 λ 1.0

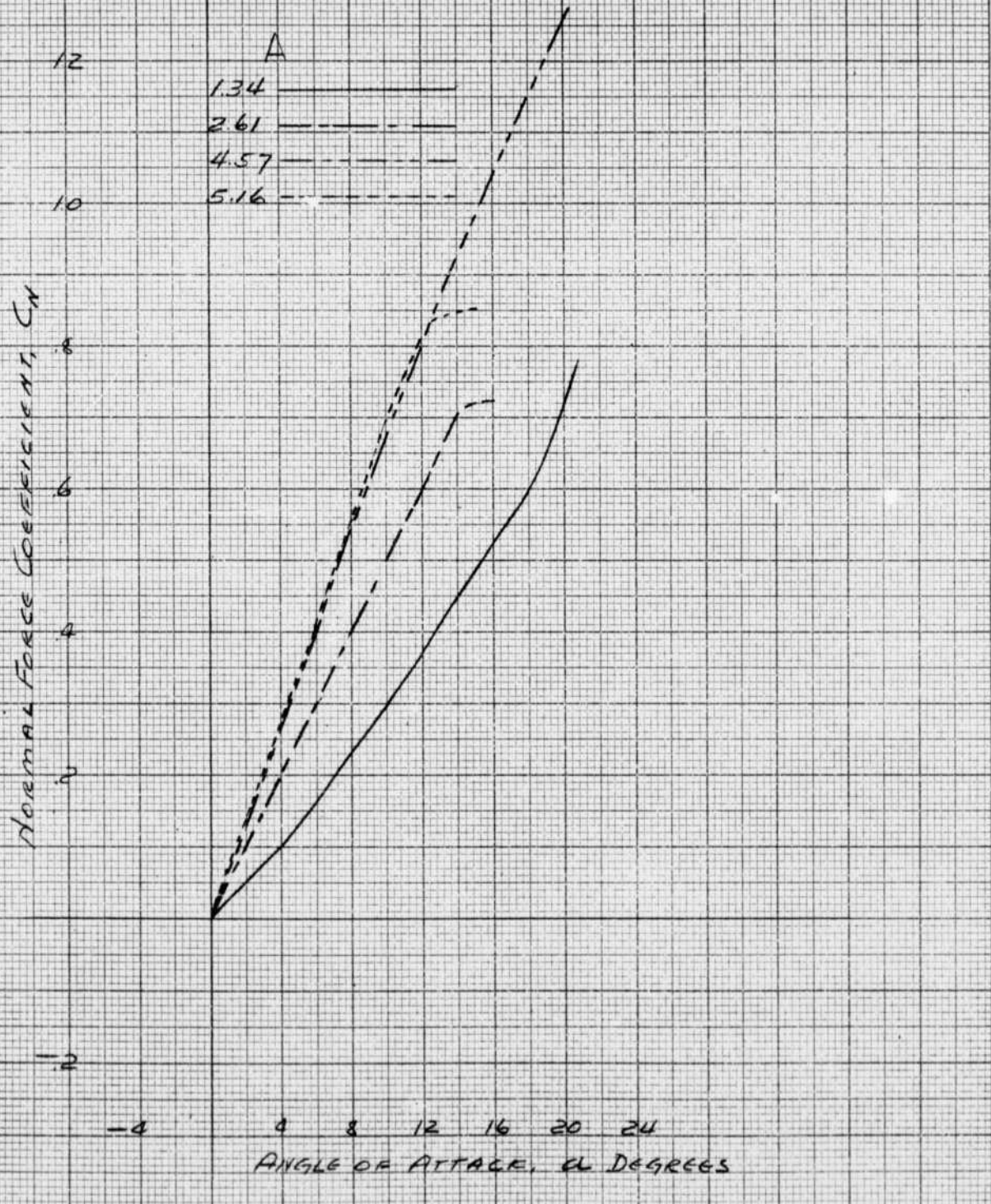


FIGURE 37C

SECTION NACA 0012

TIP SHAPE FAIRED

Λ 0°
 λ 1.0

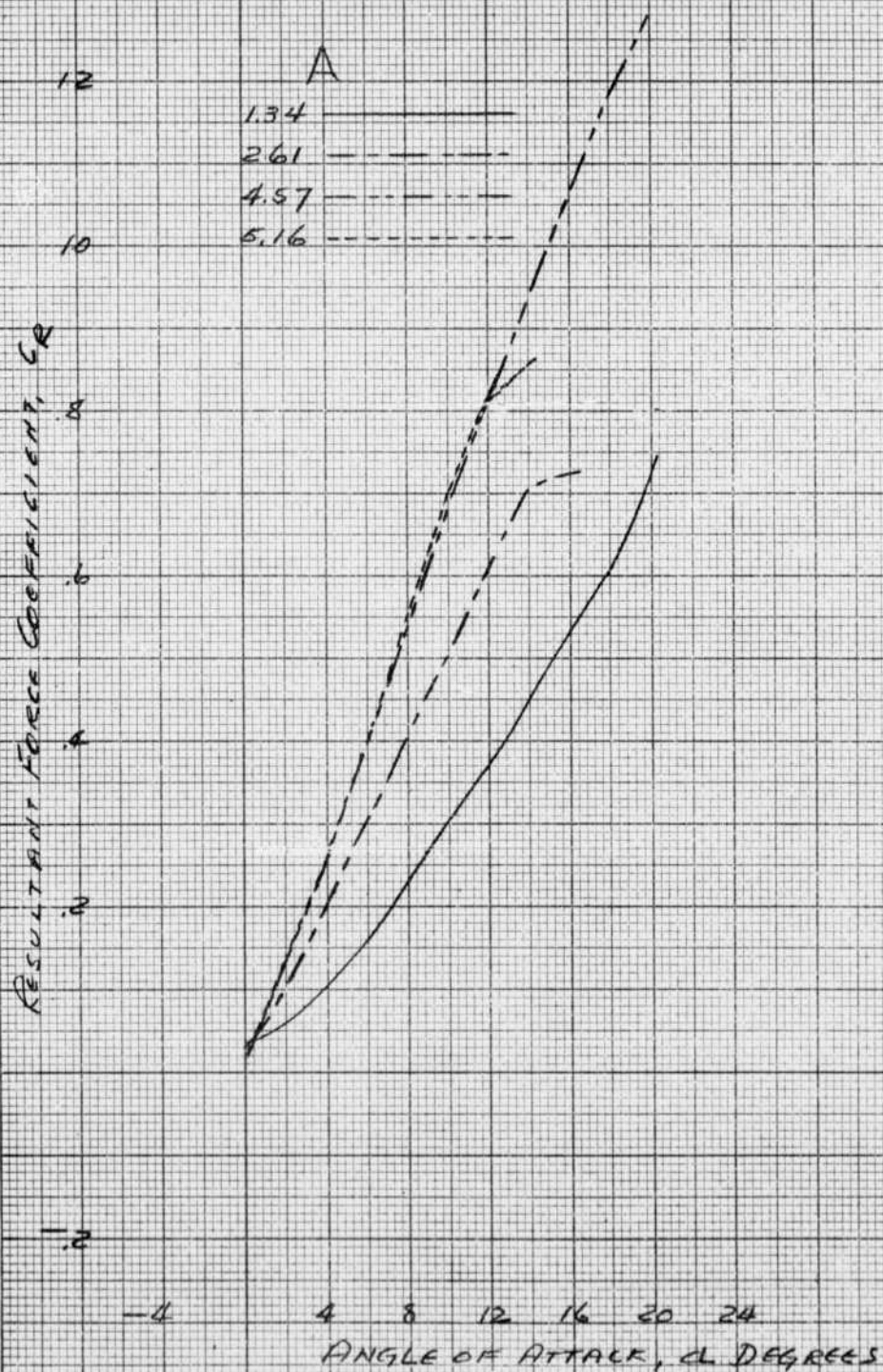


FIGURE 37D

SECTION	NACA 0012
TIP SHAPE	FAIRED
Λ	0°
λ	1.0
Δ	
1.34	—————
2.61	- - - - -
4.57	- - - - -
5.16	- - - - -

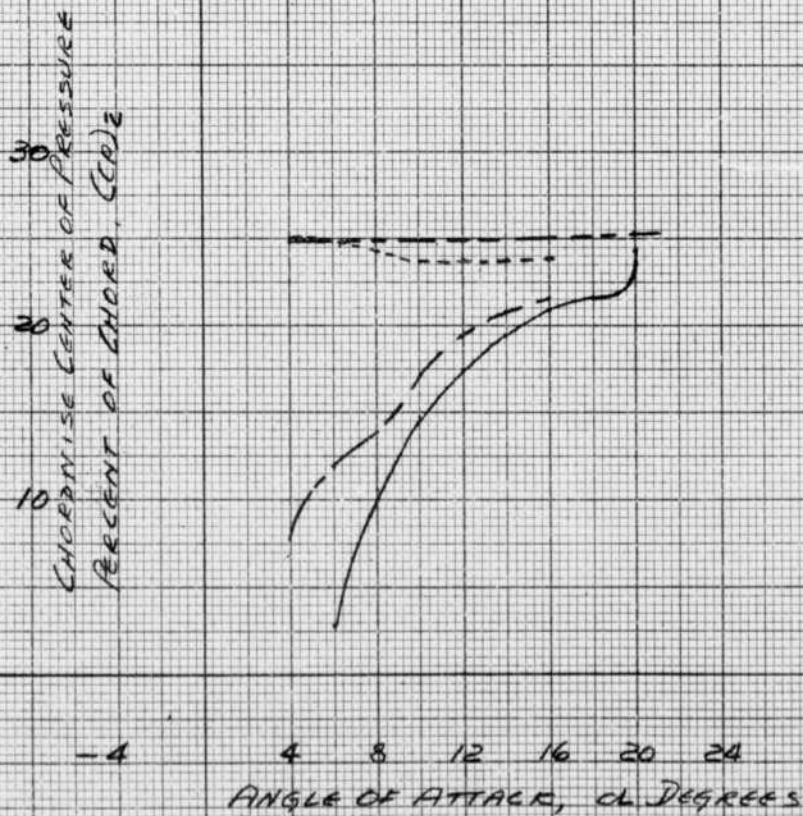


FIGURE 38

SECTION NACA 0012

TIP SHAPE FAIRED

Λ 45

λ 1.0

A

1.34 —————
2.61 - - - - -
5.16 - - - - -

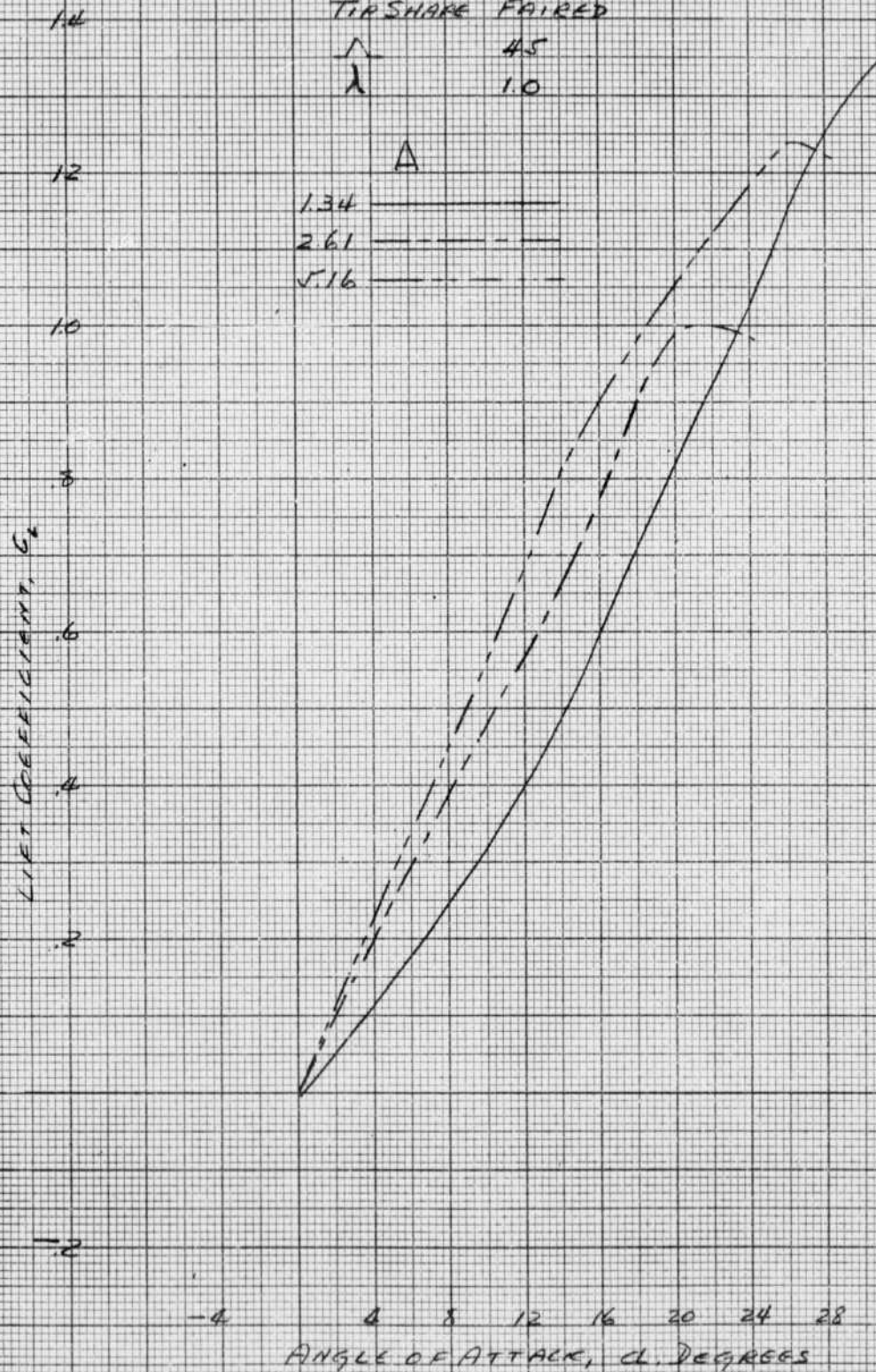
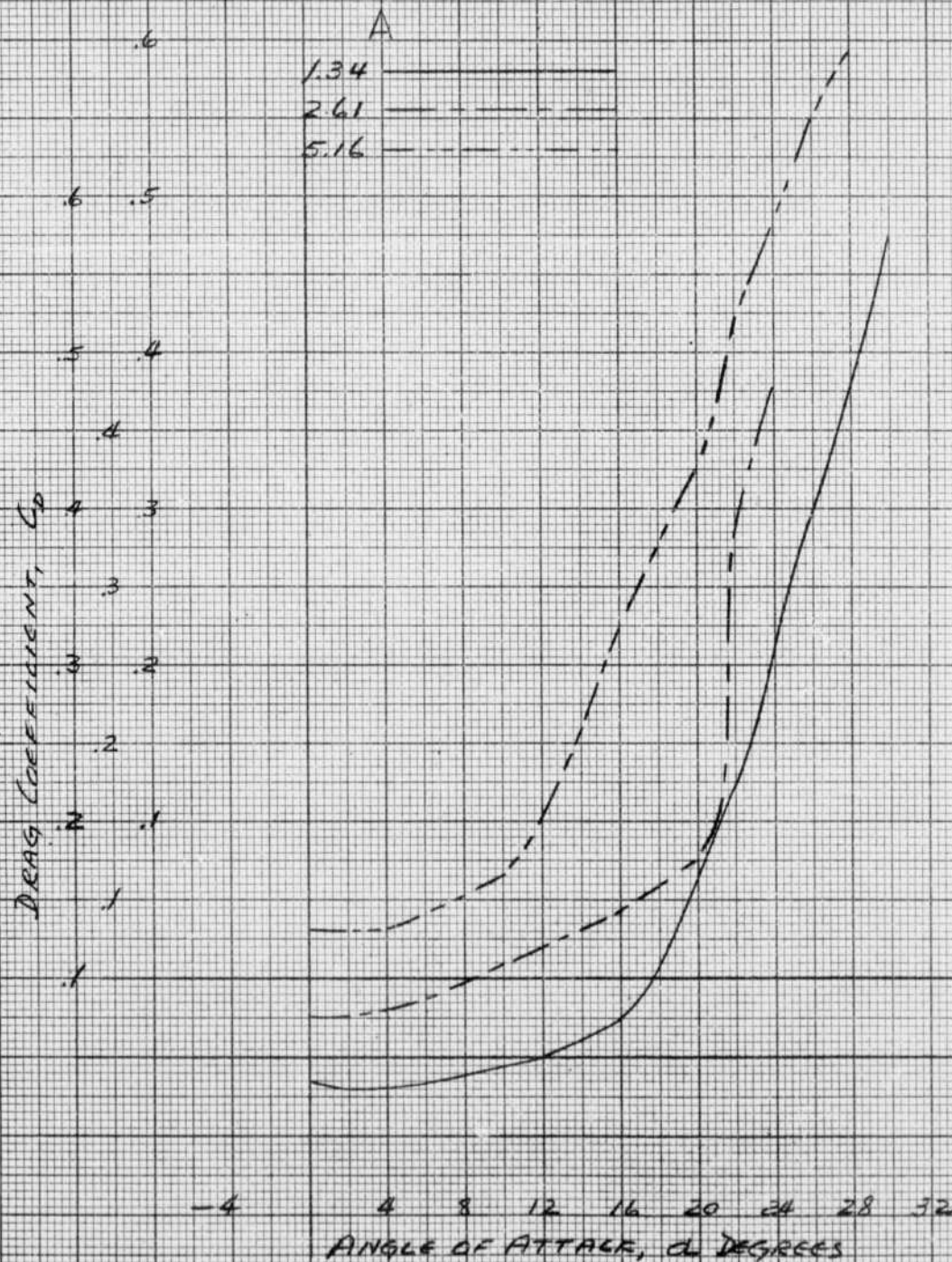


FIGURE 38A

SECTION NACA 0012
TIP SHAPE FAIRED Λ 45
 λ 10

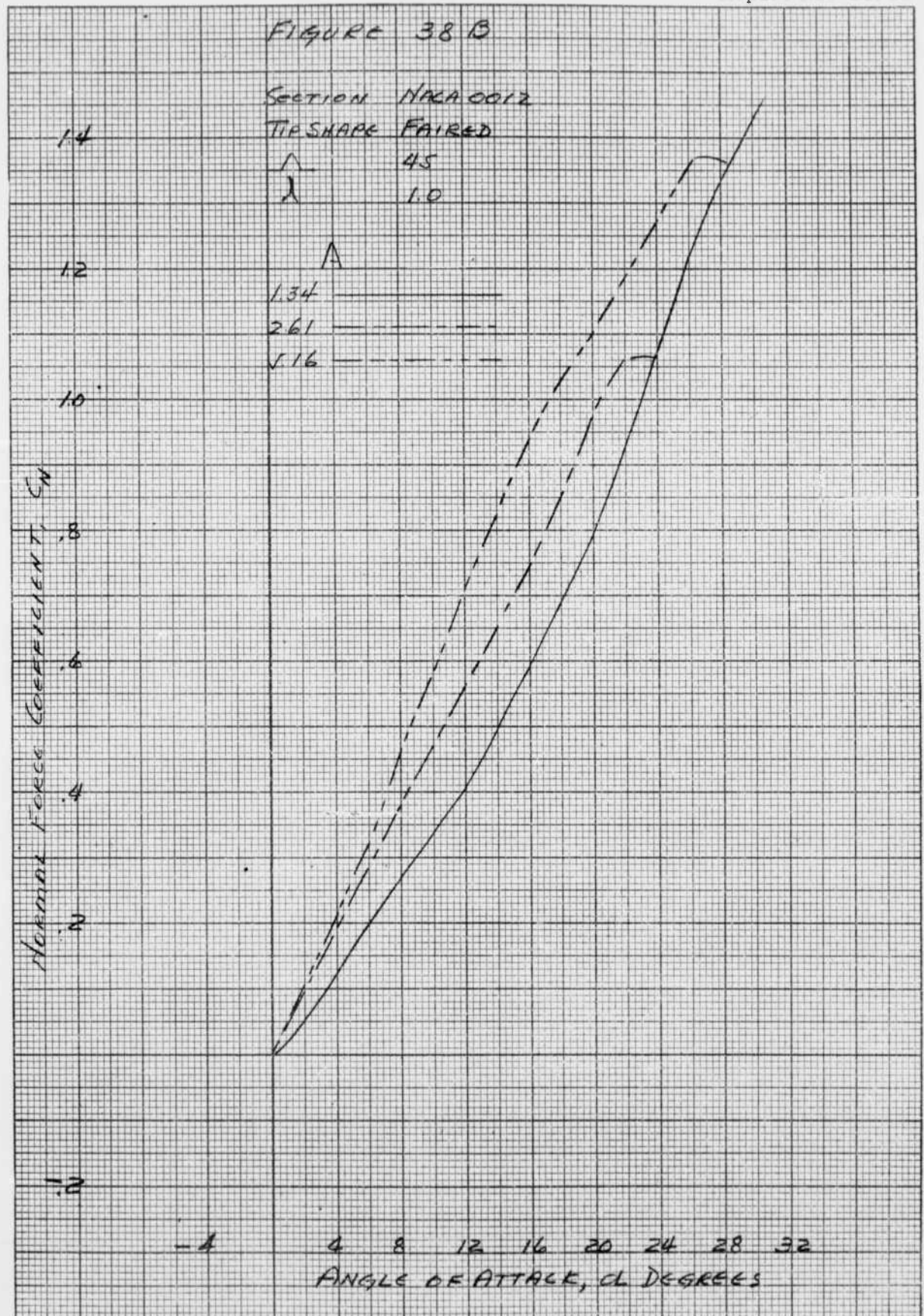


FIGURE 38C

SECTION NACA 0012
TIP SHAPE FAIRED
 Δ 45
 λ 1.0

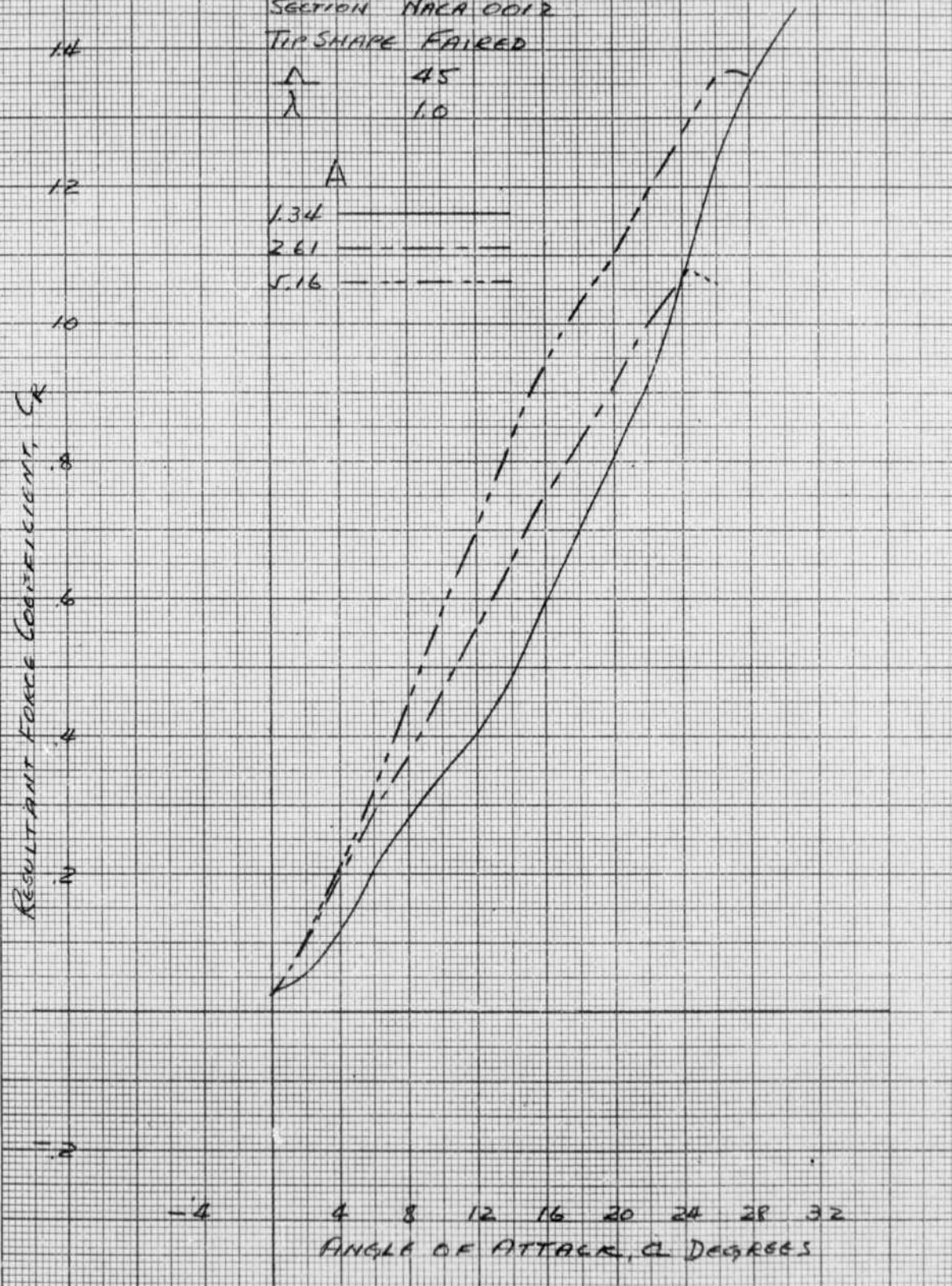


FIGURE 38D

SECTION NACA0012
TIP SHAPE FAIRED
 Λ 45
 λ 1.0

A

1.34 —————
2.61 — — — — —
5.16 — — — — —

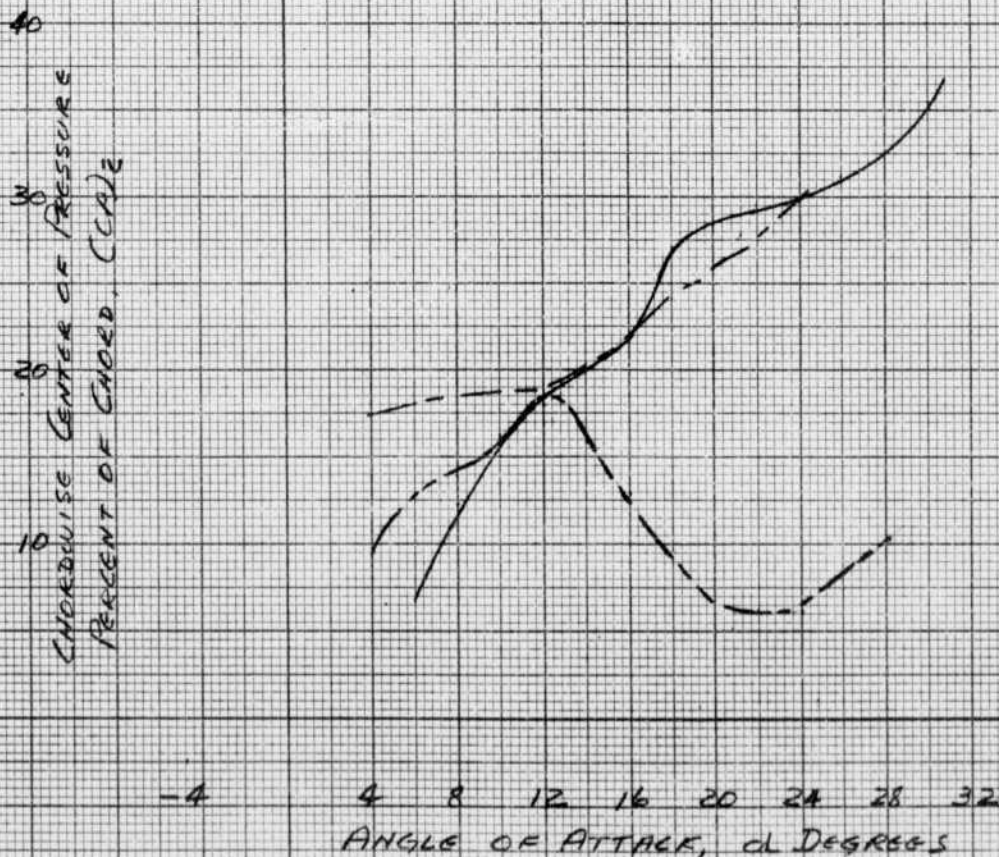


FIGURE 39

SECTION NACA 0012

TIP SHAPE FAIRED

Δ 45

$A \lambda$

300 0

261 0.25

261 0.5

261 1.0

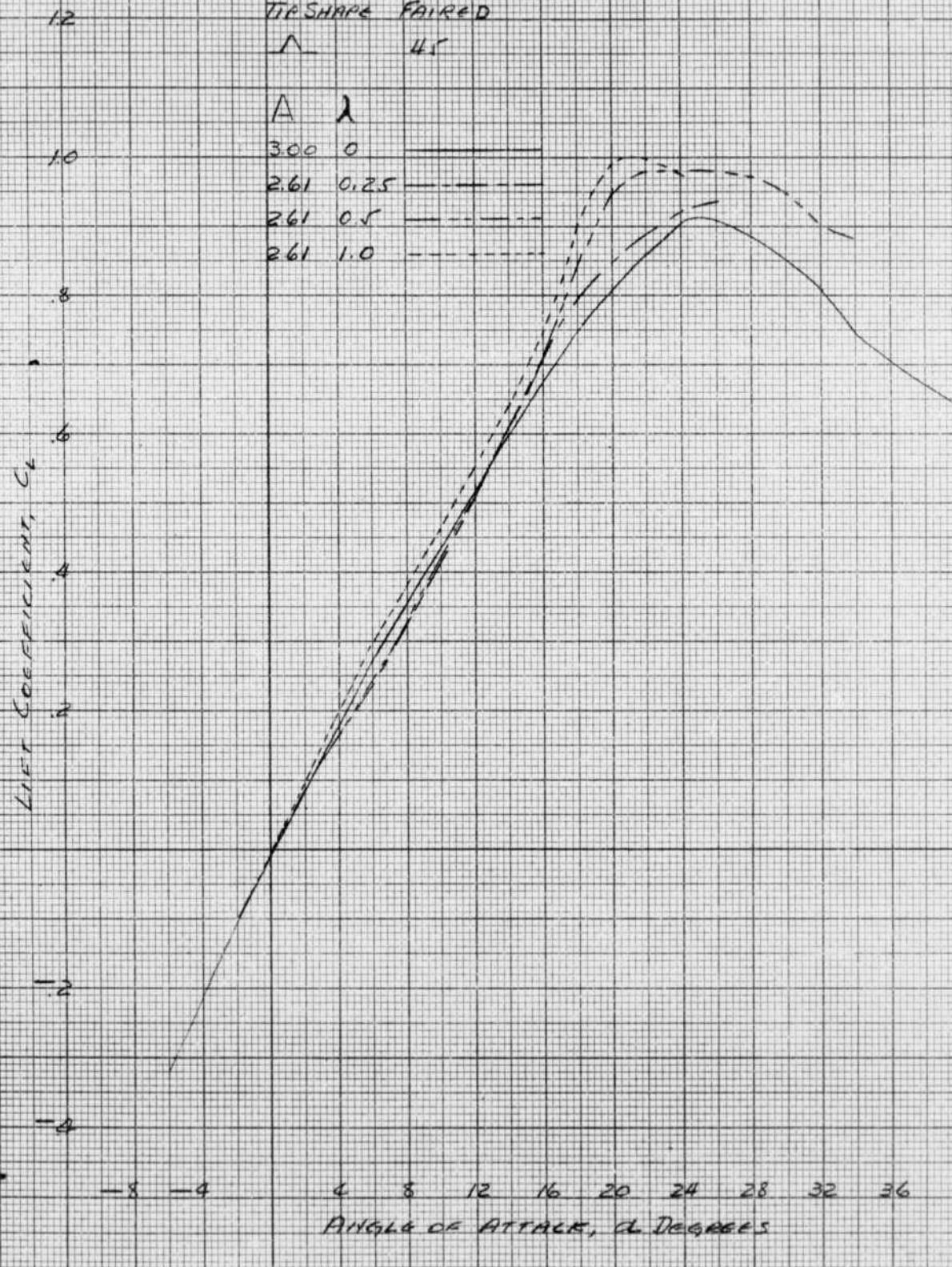


FIGURE 39A

SECTION NACA 0012

TIP SHAPE FAIRED

Λ 45

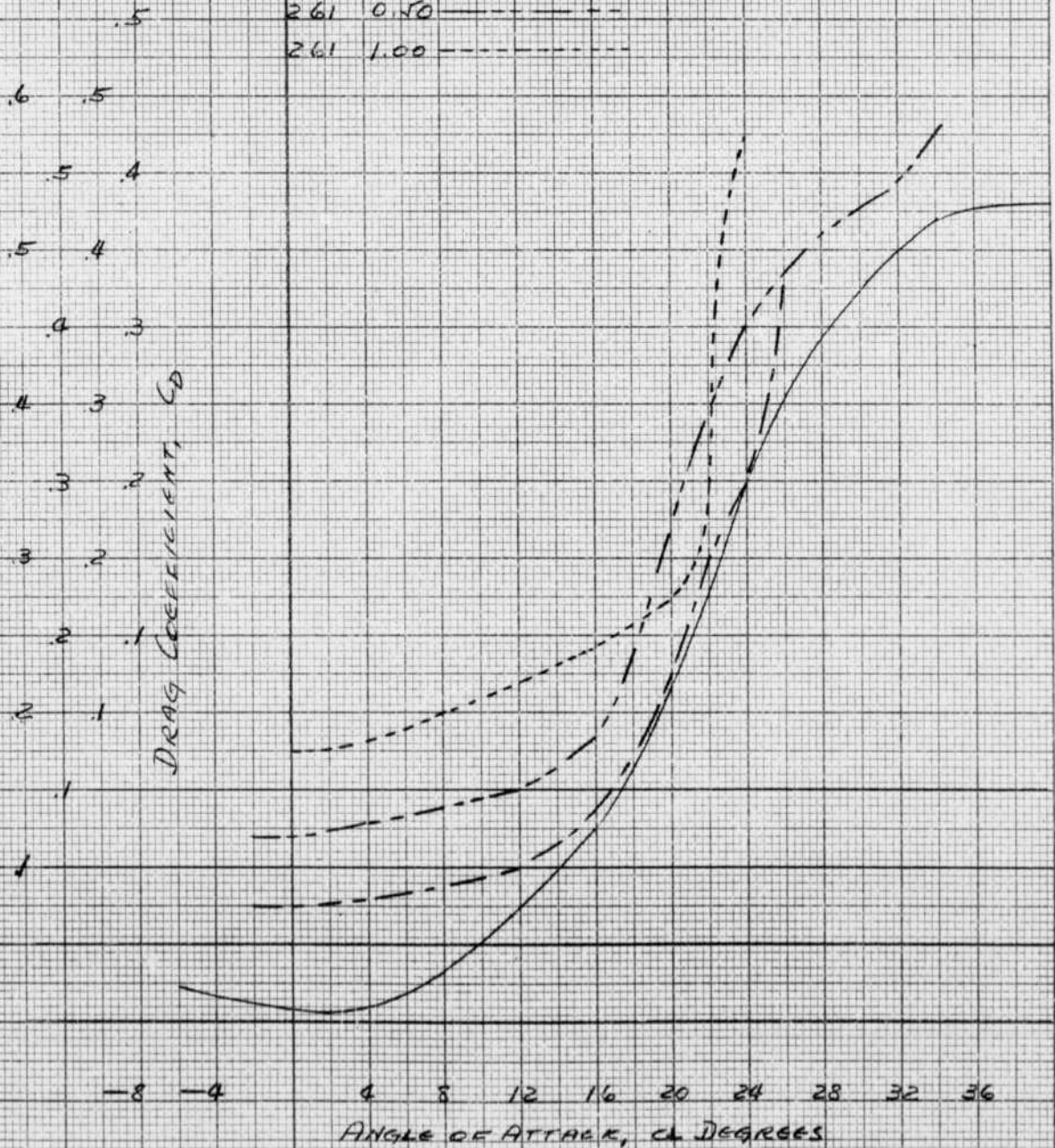
A λ

300 0 —————

261 0.25 ————

261 0.50 - - - - -

261 1.00 - - - - -



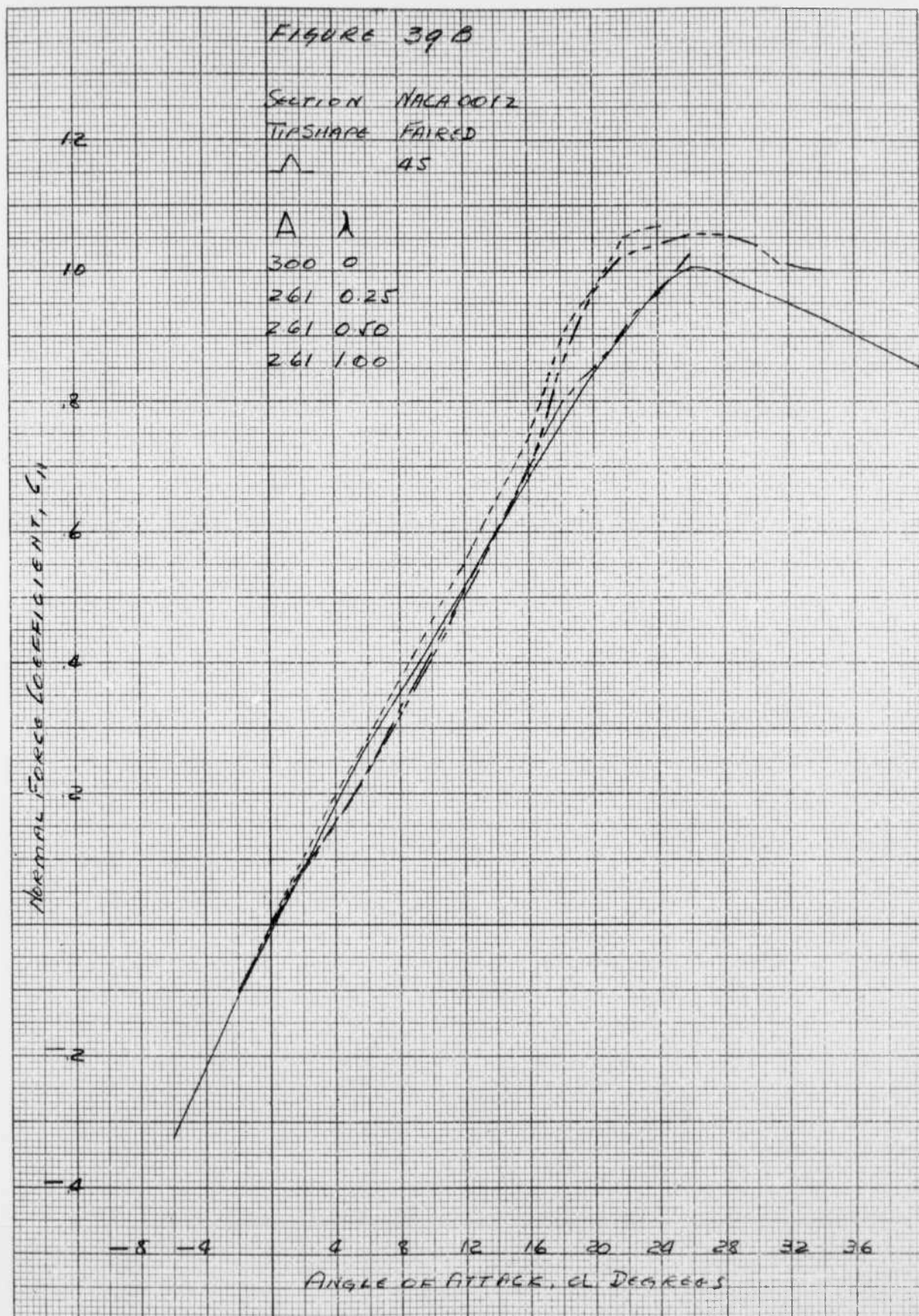


FIGURE 39C

SECTION NACA 0012
TIP SHAPE FAIRED
 Λ 45

A	λ
300	0
261	0.25
261	0.50
261	1.00

12

10

RESULTANT FORCE COEFFICIENT, C_R

-8 -4 4 8 12 16 20 24 28 32 36

ANGLE OF ATTACK, α DEGREES

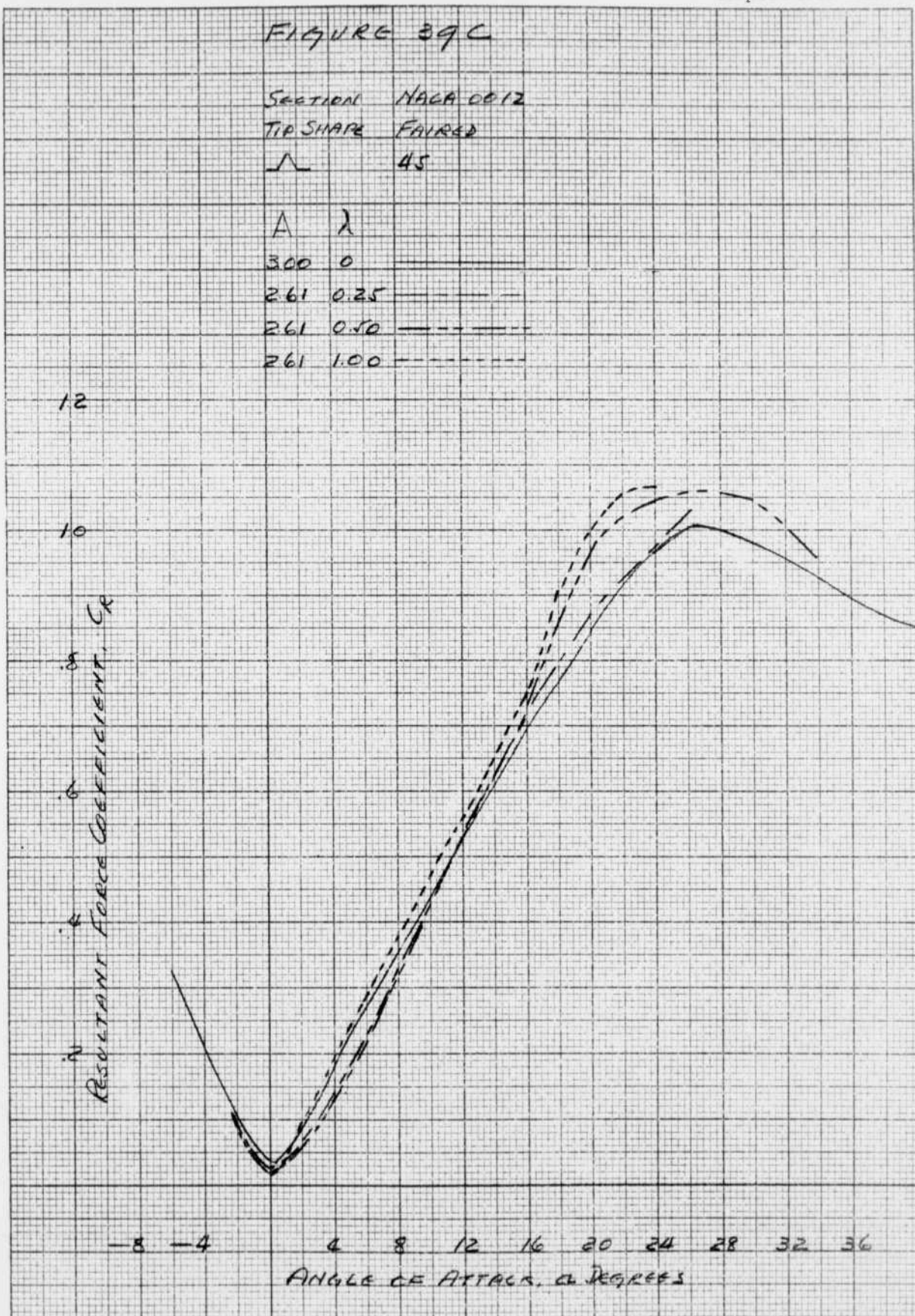
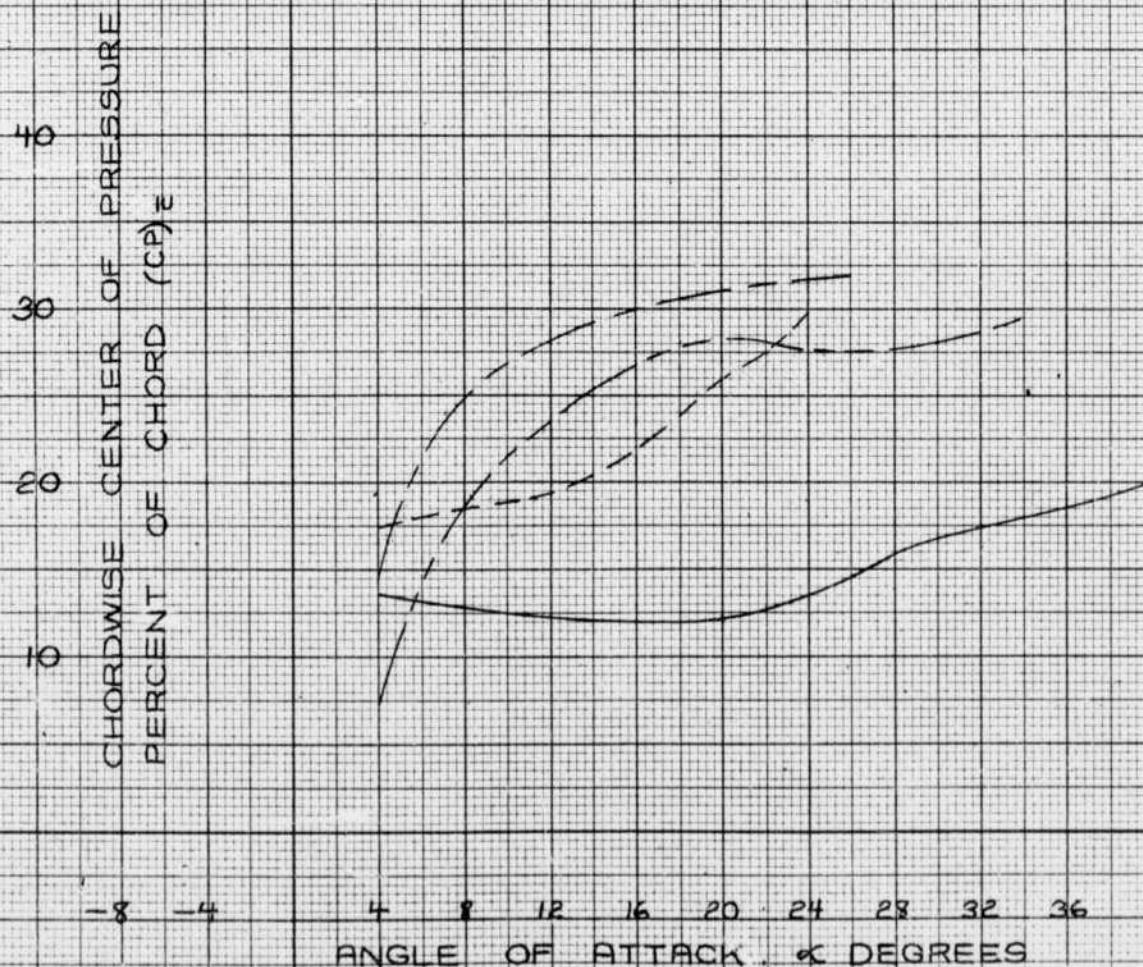


FIGURE 39 D

SECTION NACA 0012
TIP SHAPE FAIRED
 Λ 45°

A	λ	
3.00	0	—————
2.61	0.25	-----
2.61	0.50	-----
2.61	1.00	-----



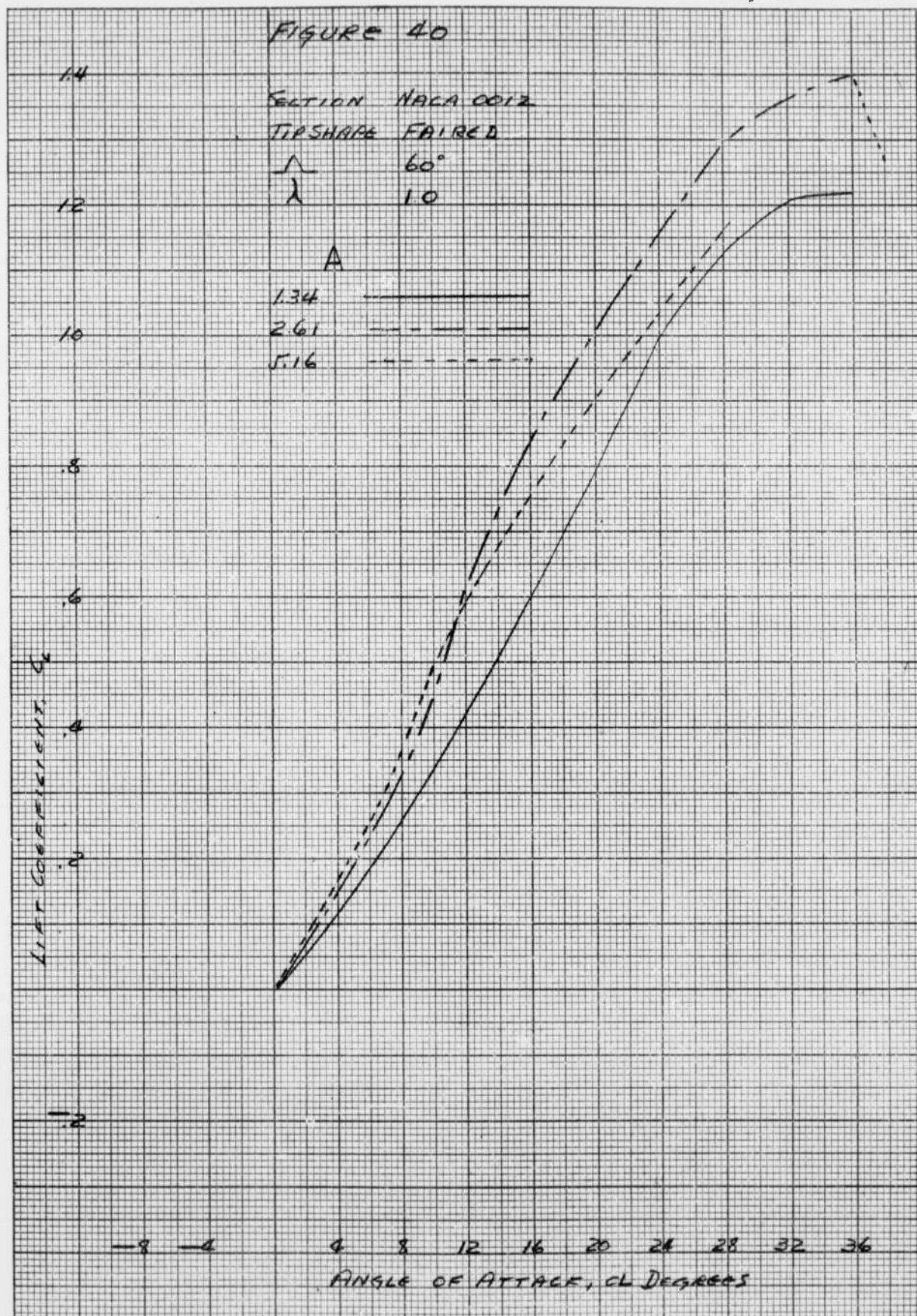


FIGURE 40A

SECTION NACA 0012

TIP SHAPE FAIRED

Λ 60°

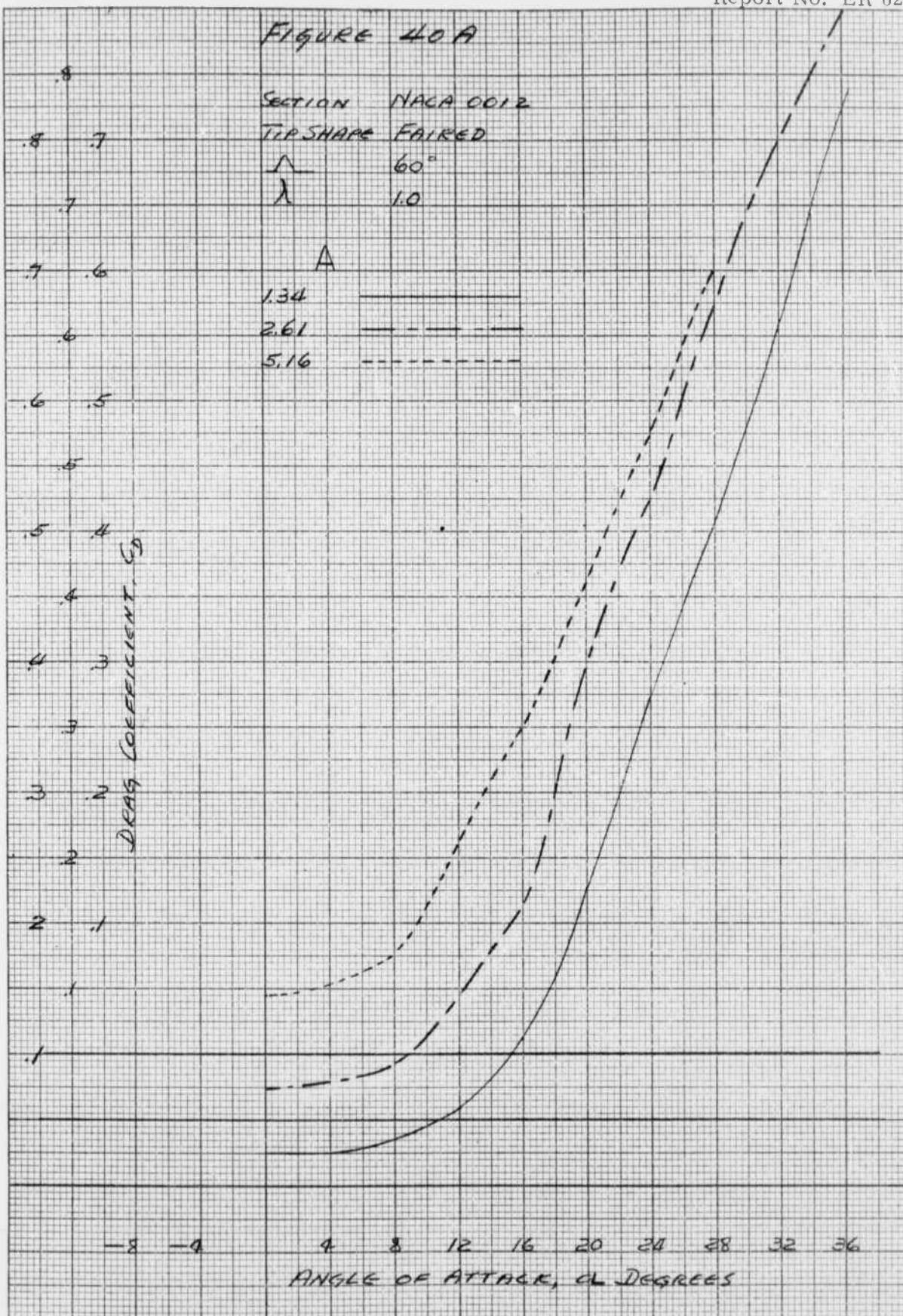
λ 1.0

A

1.34

2.61

5.16



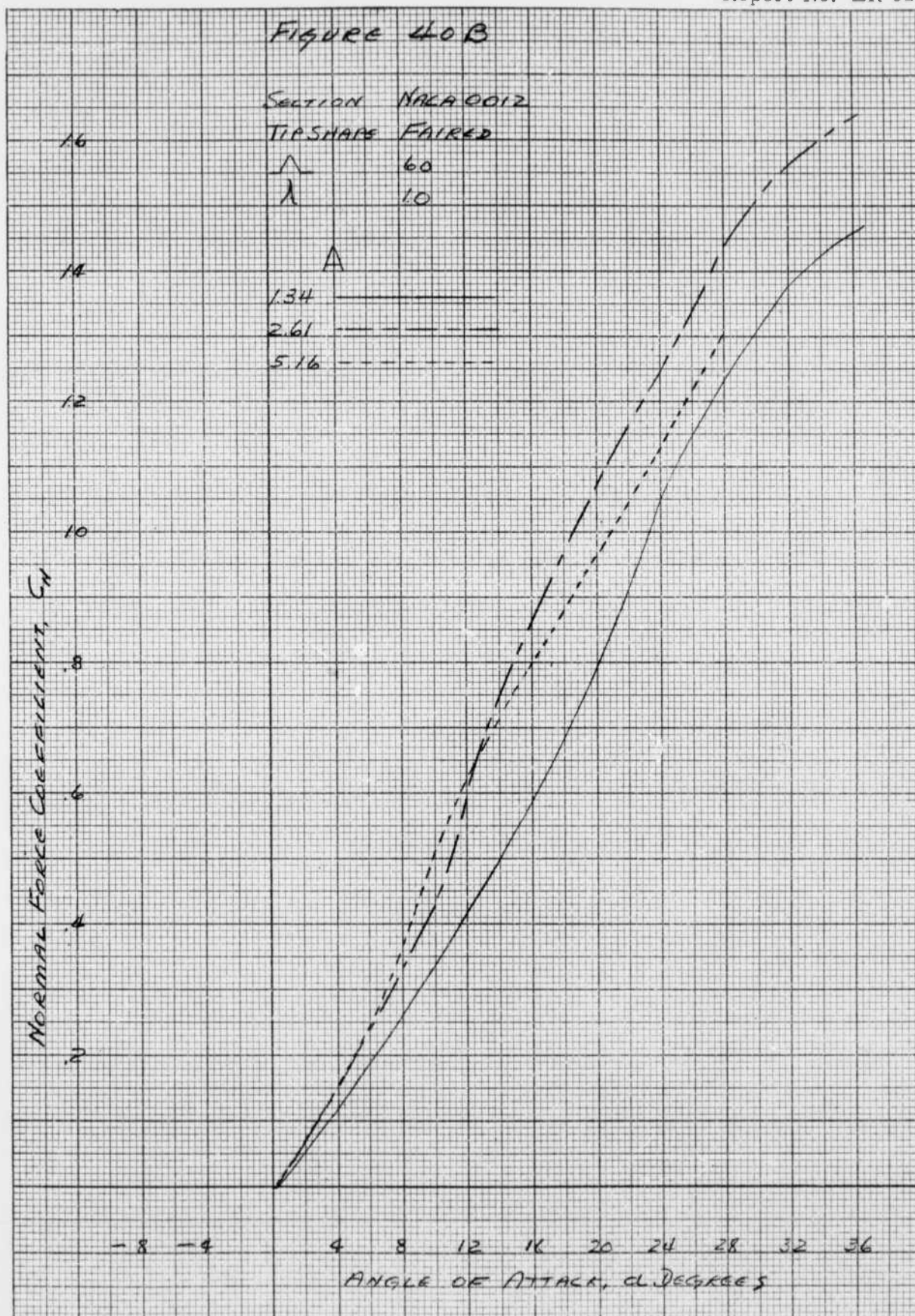


Figure 40C

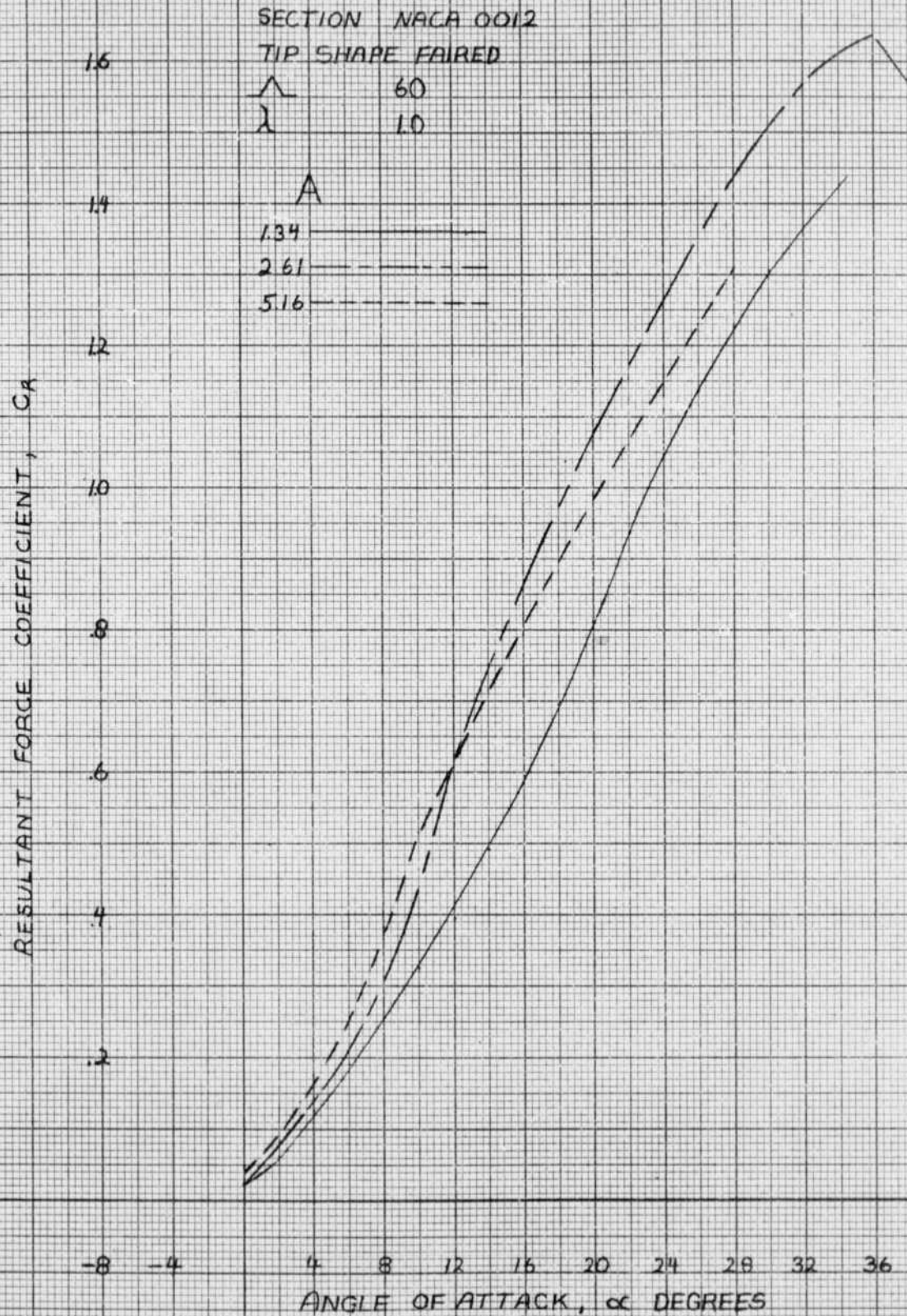


FIGURE 40D

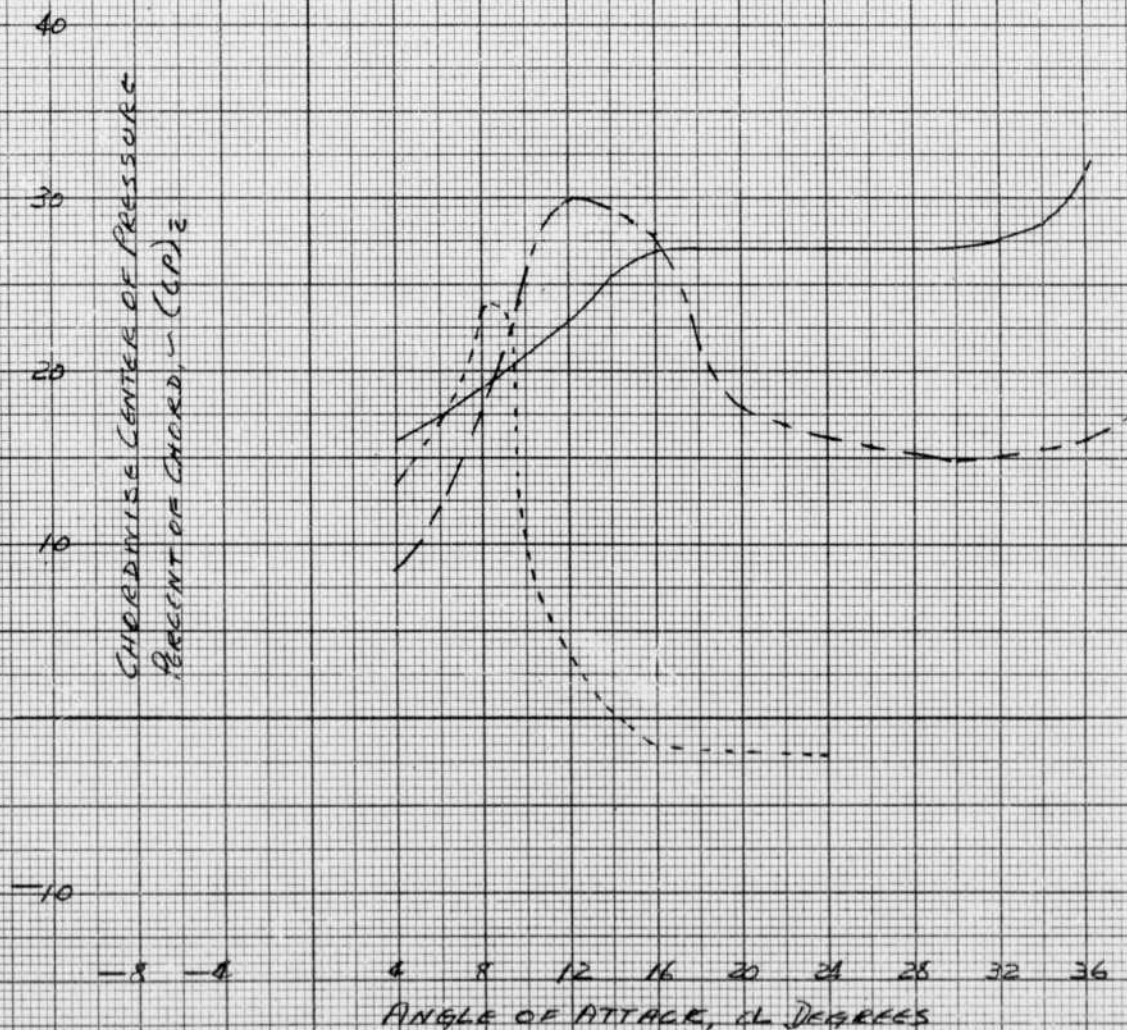
SECTION	NACA 0012
TIP SHAPE	FAIRED
Λ	60
λ	1.0

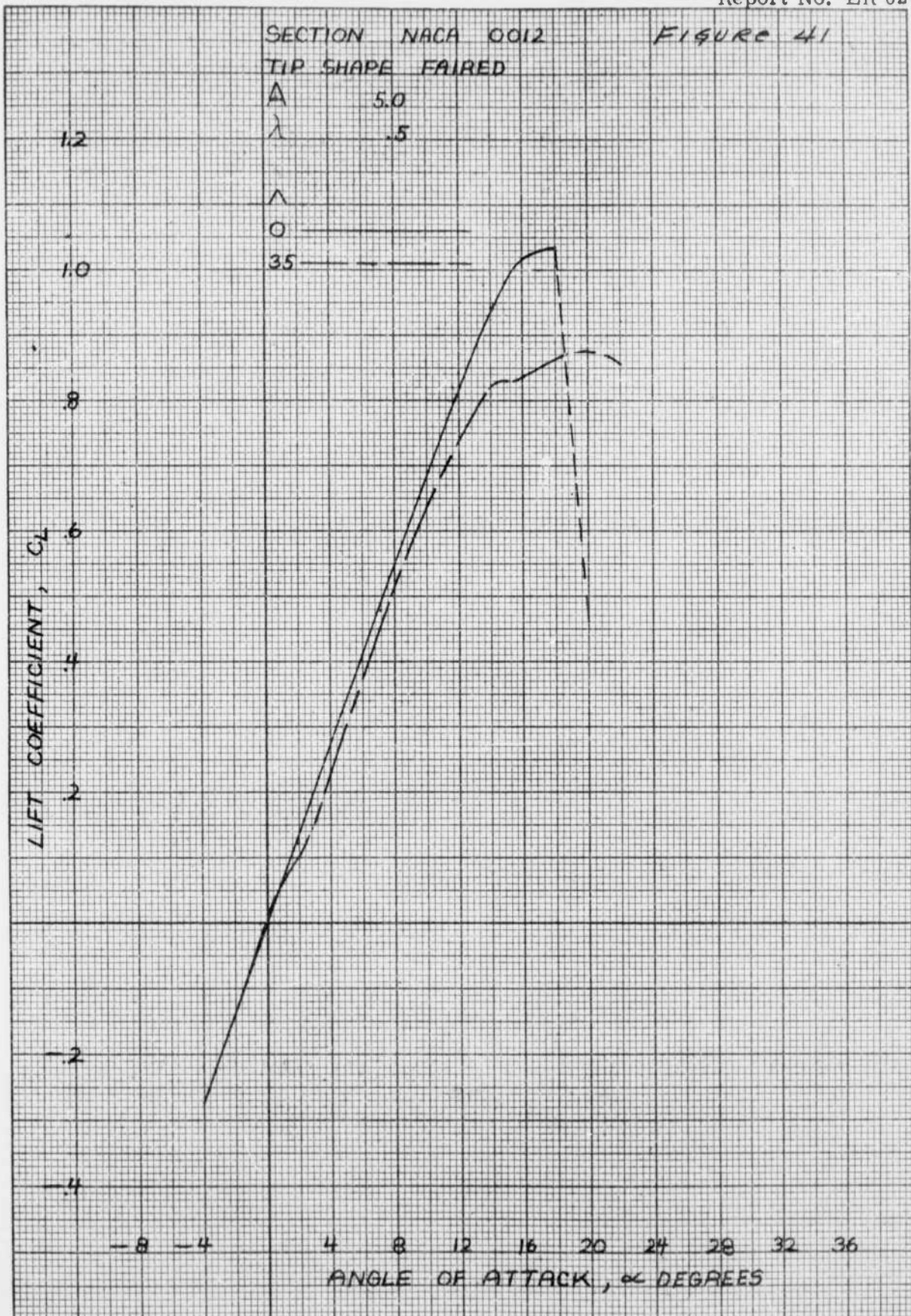
A

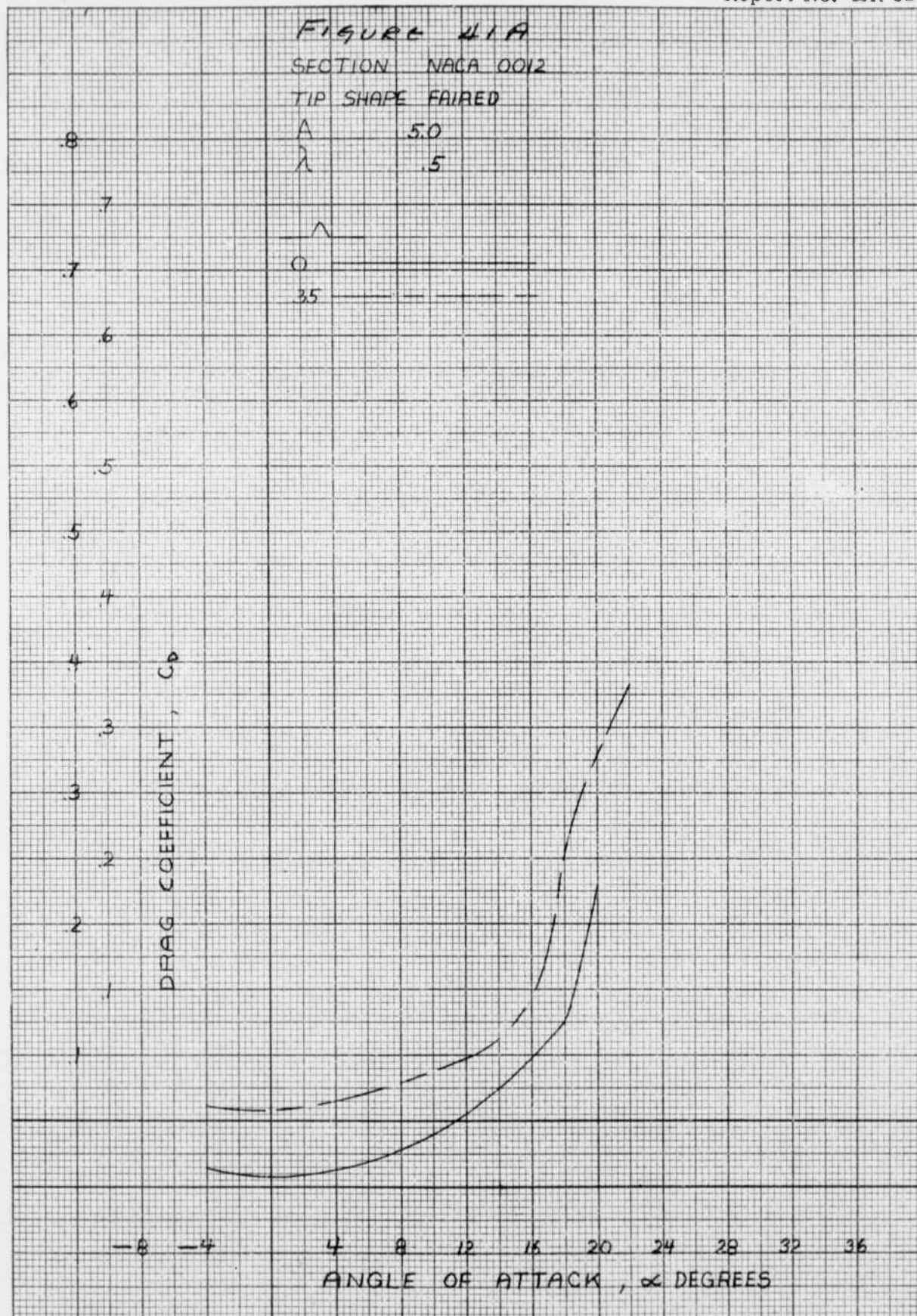
1.34

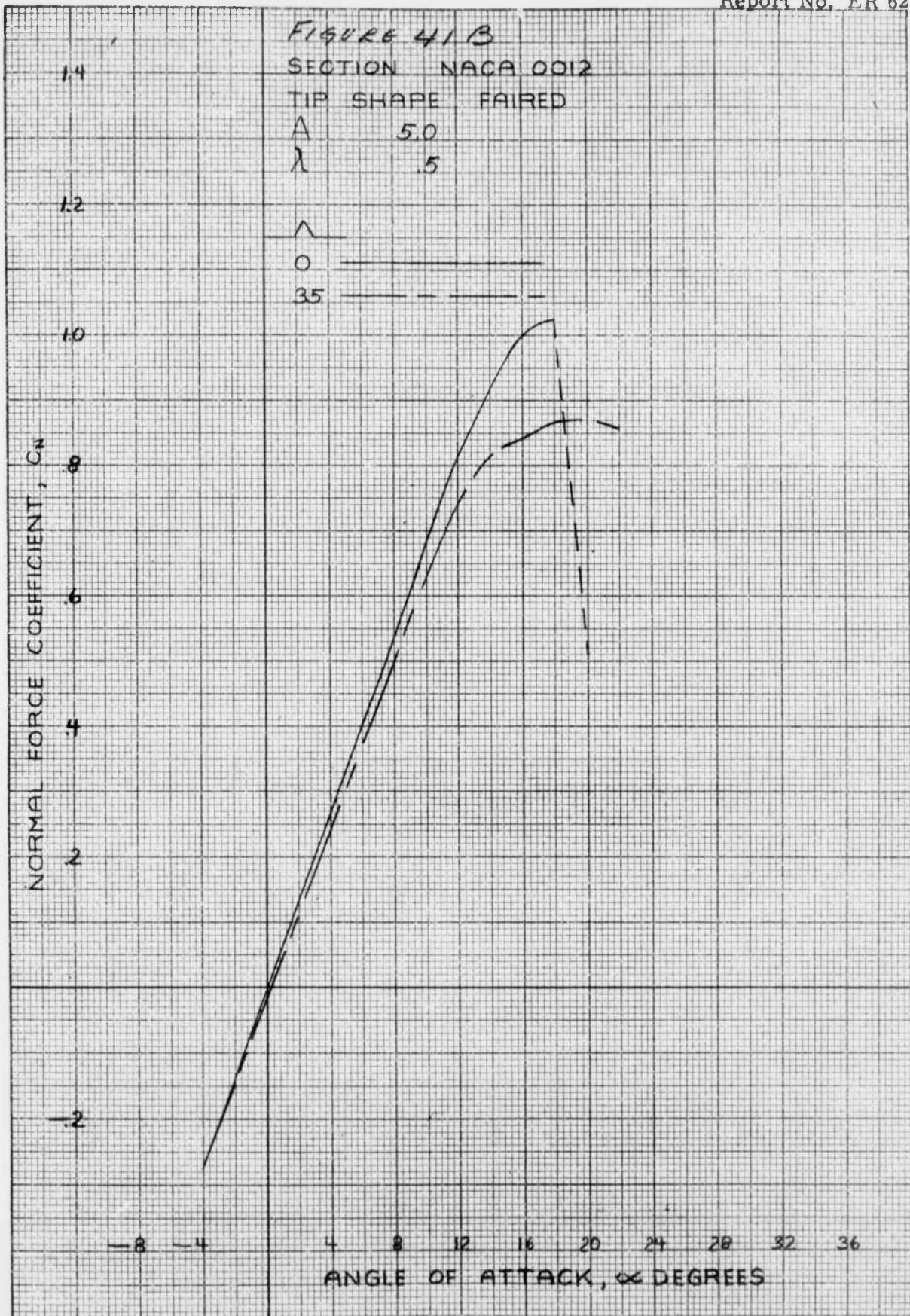
2.61

5.16









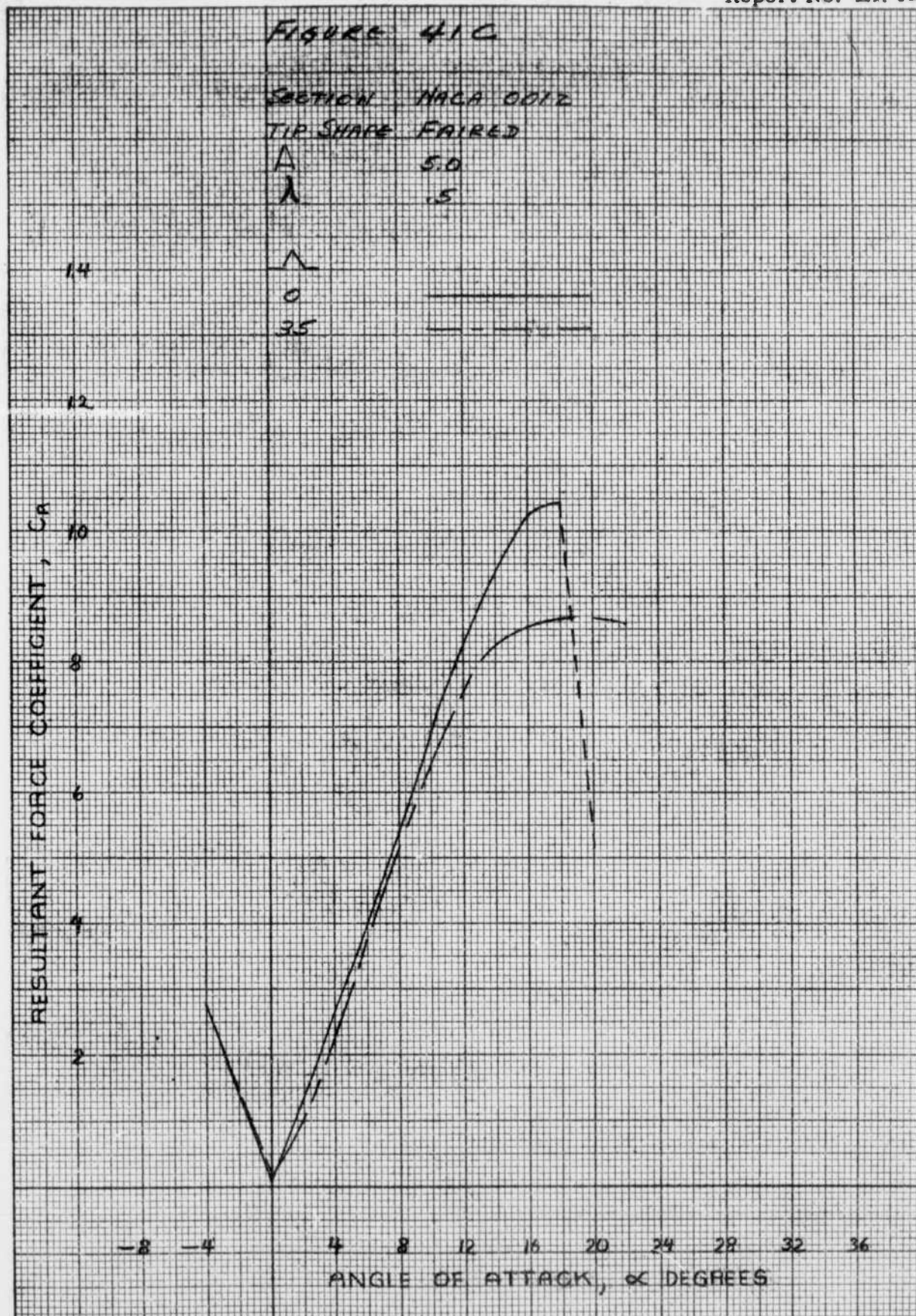


FIGURE 41D
SECTION NACA 0012
TIP SHAPE FAIRED
A 5.0
 λ 5
 Λ
0 _____
35 _____

CHORDWISE CENTER OF PRESSURE
PERCENT OF CHORD, (C.P.) \bar{x}

40

30

20

10

-8

-4

4

8

12

16

20

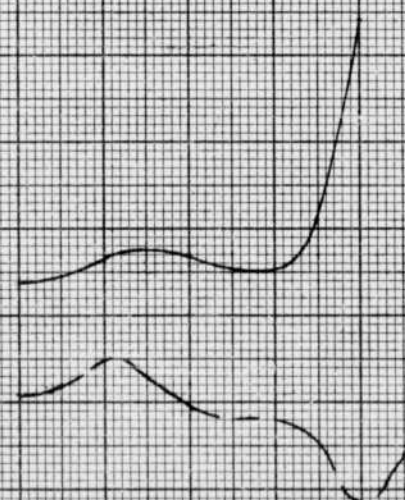
24

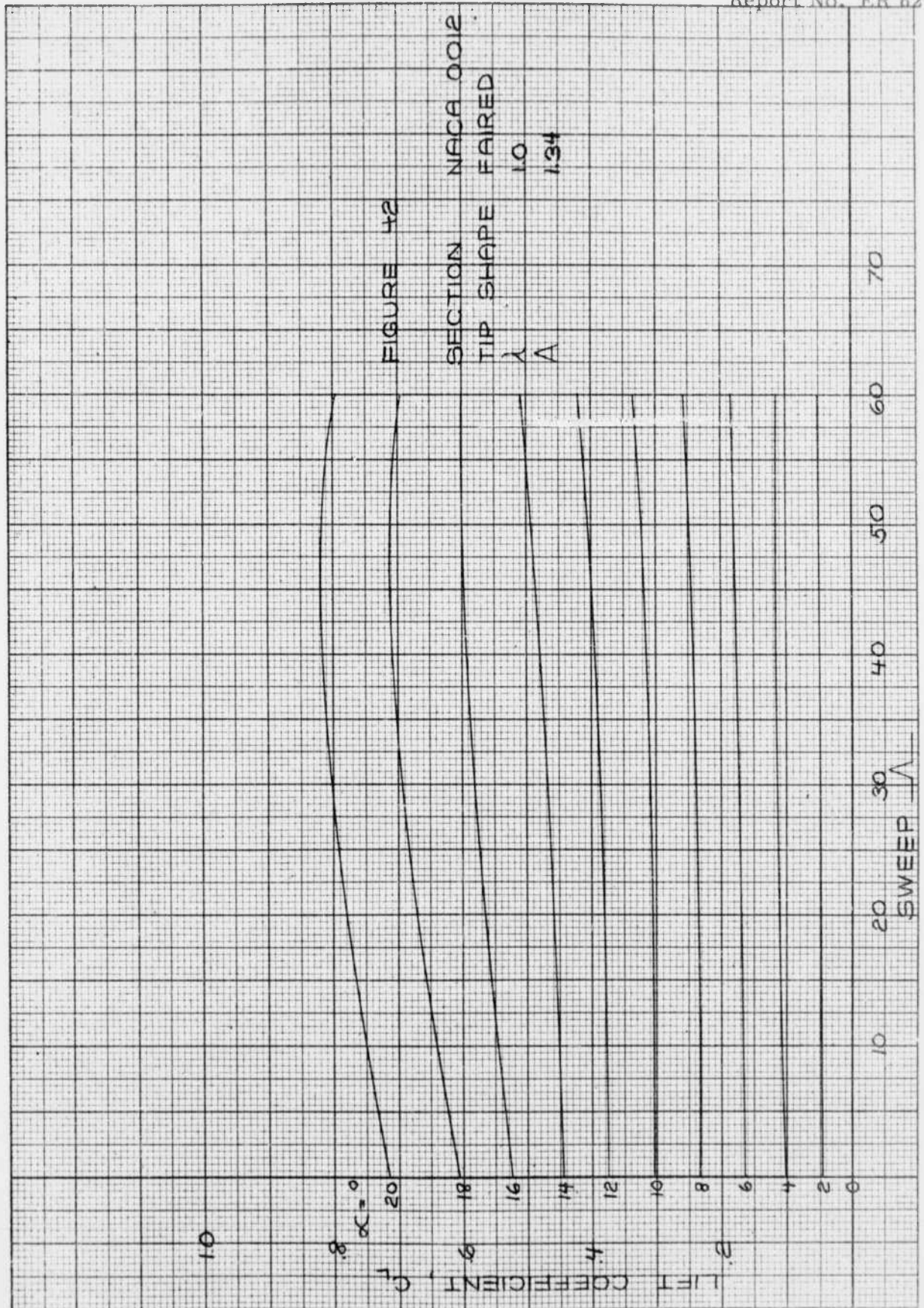
28

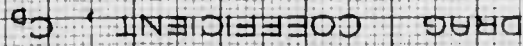
32

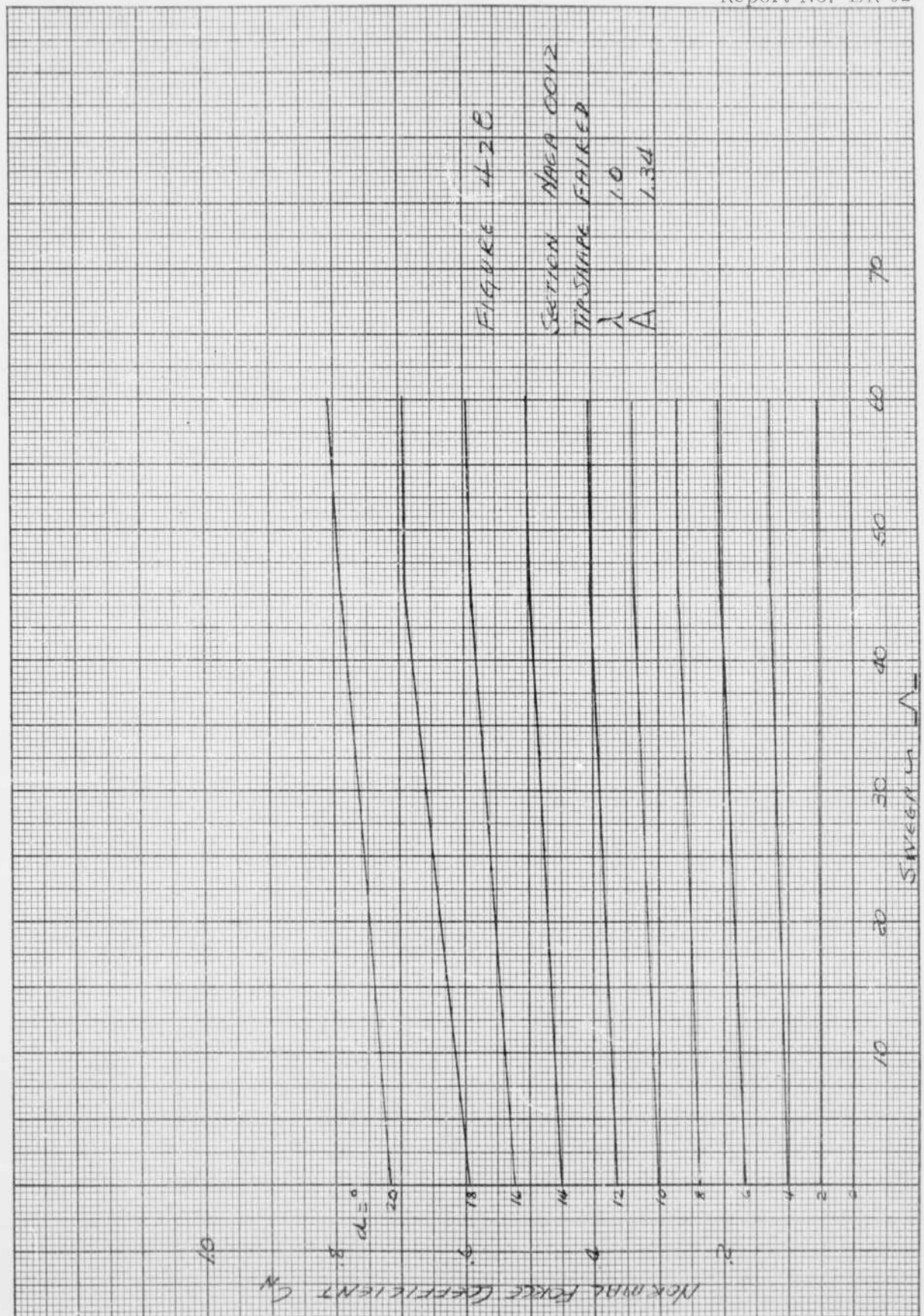
36

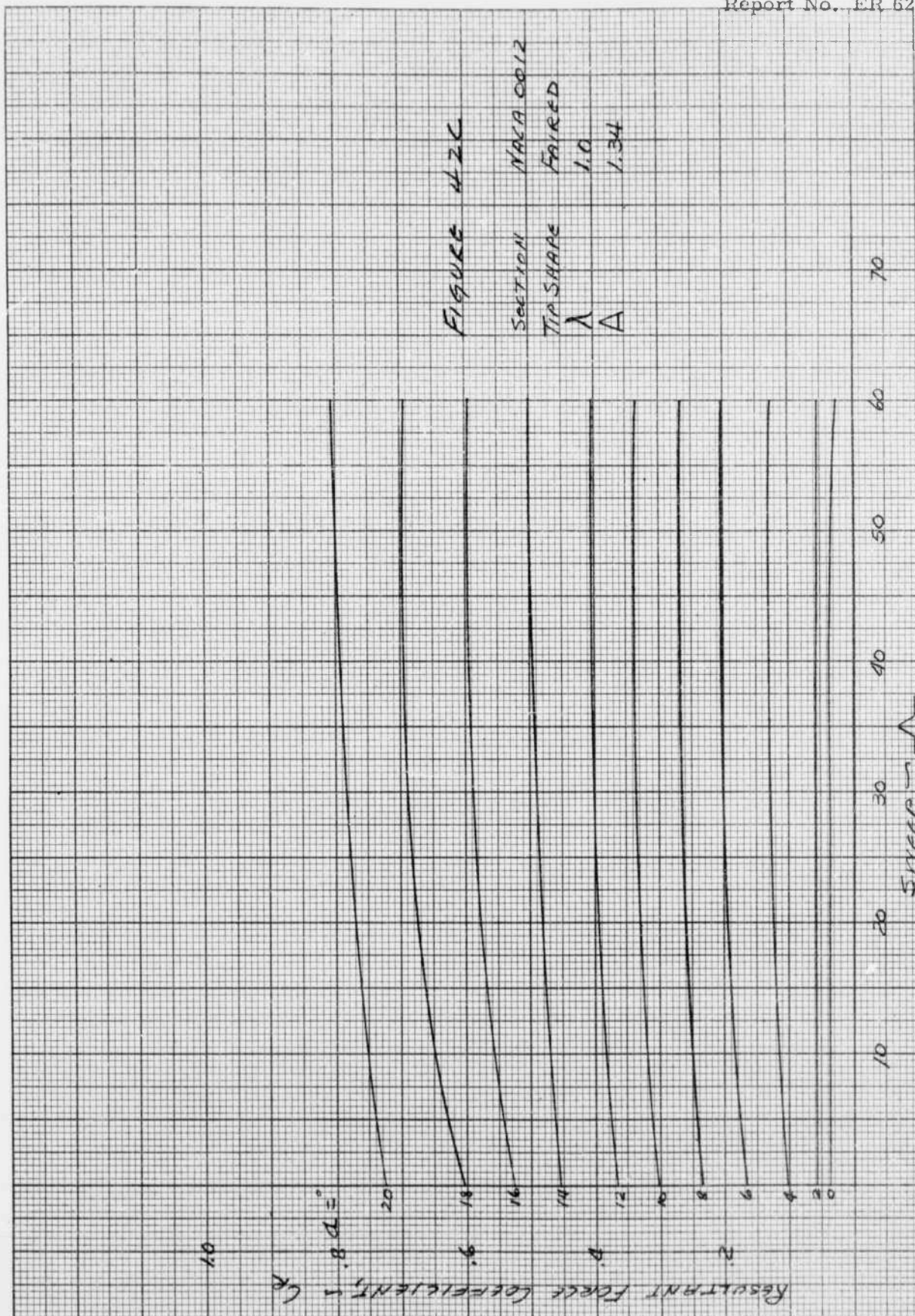
ANGLE OF ATTACK, α DEGREES

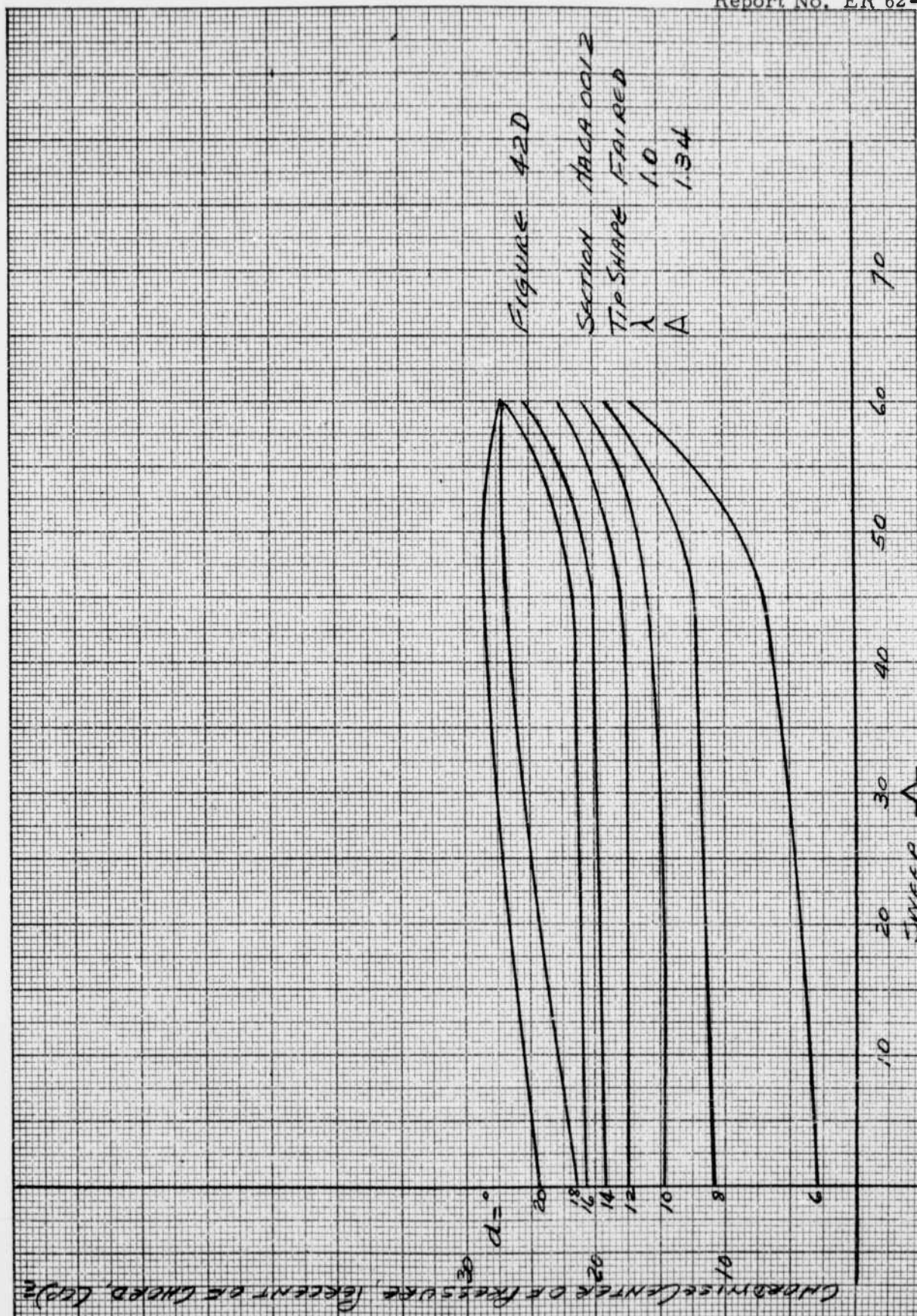


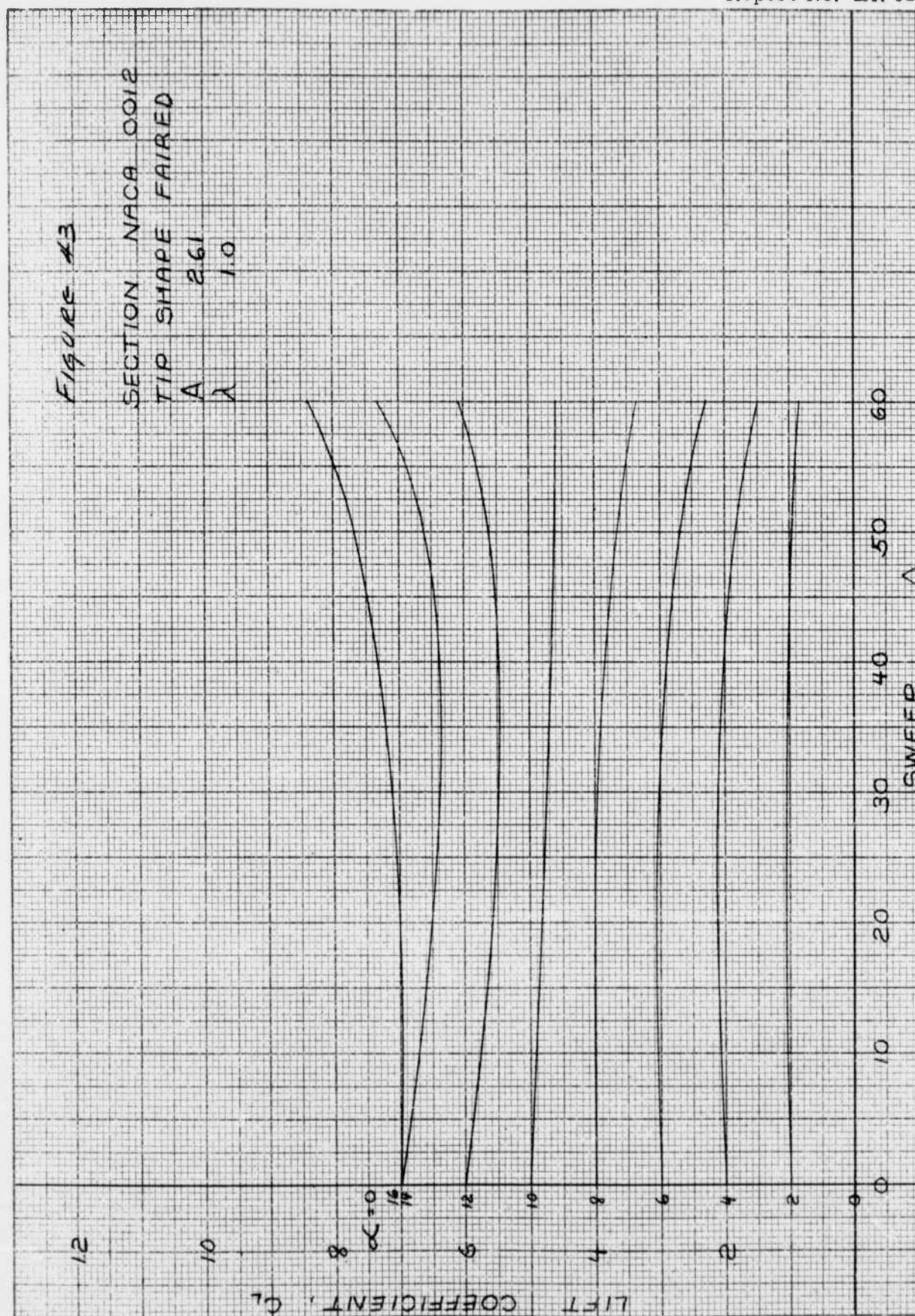


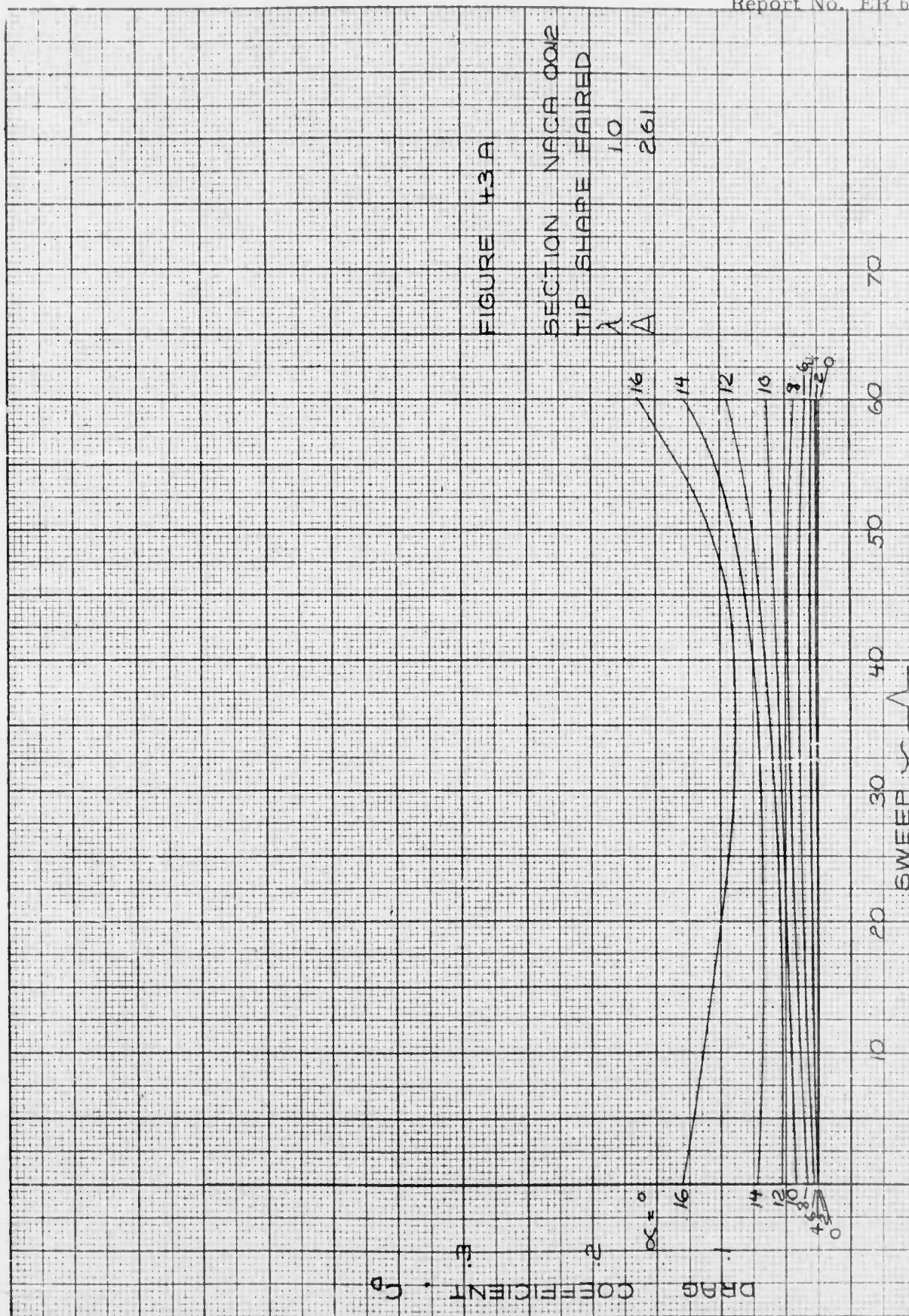


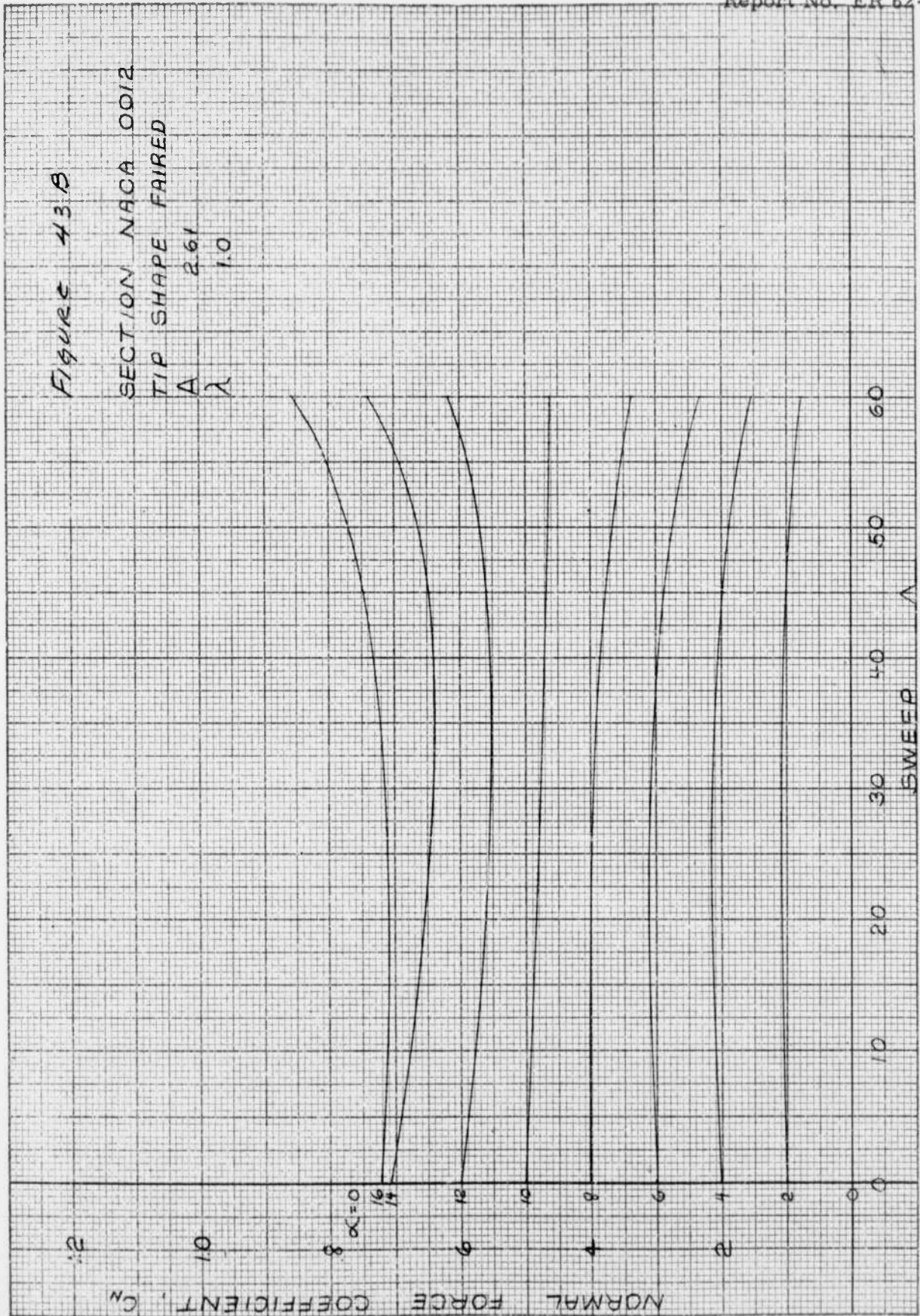


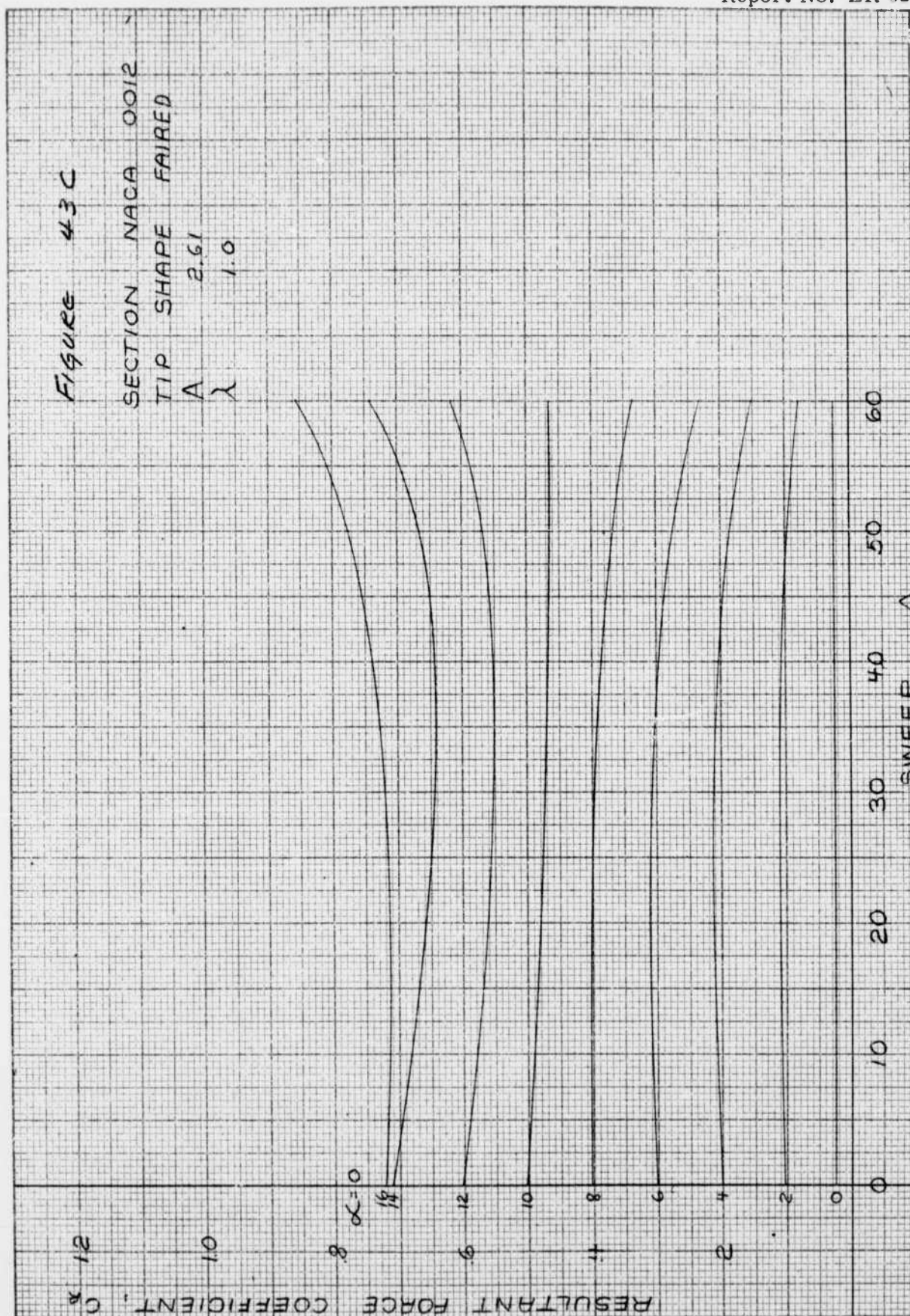


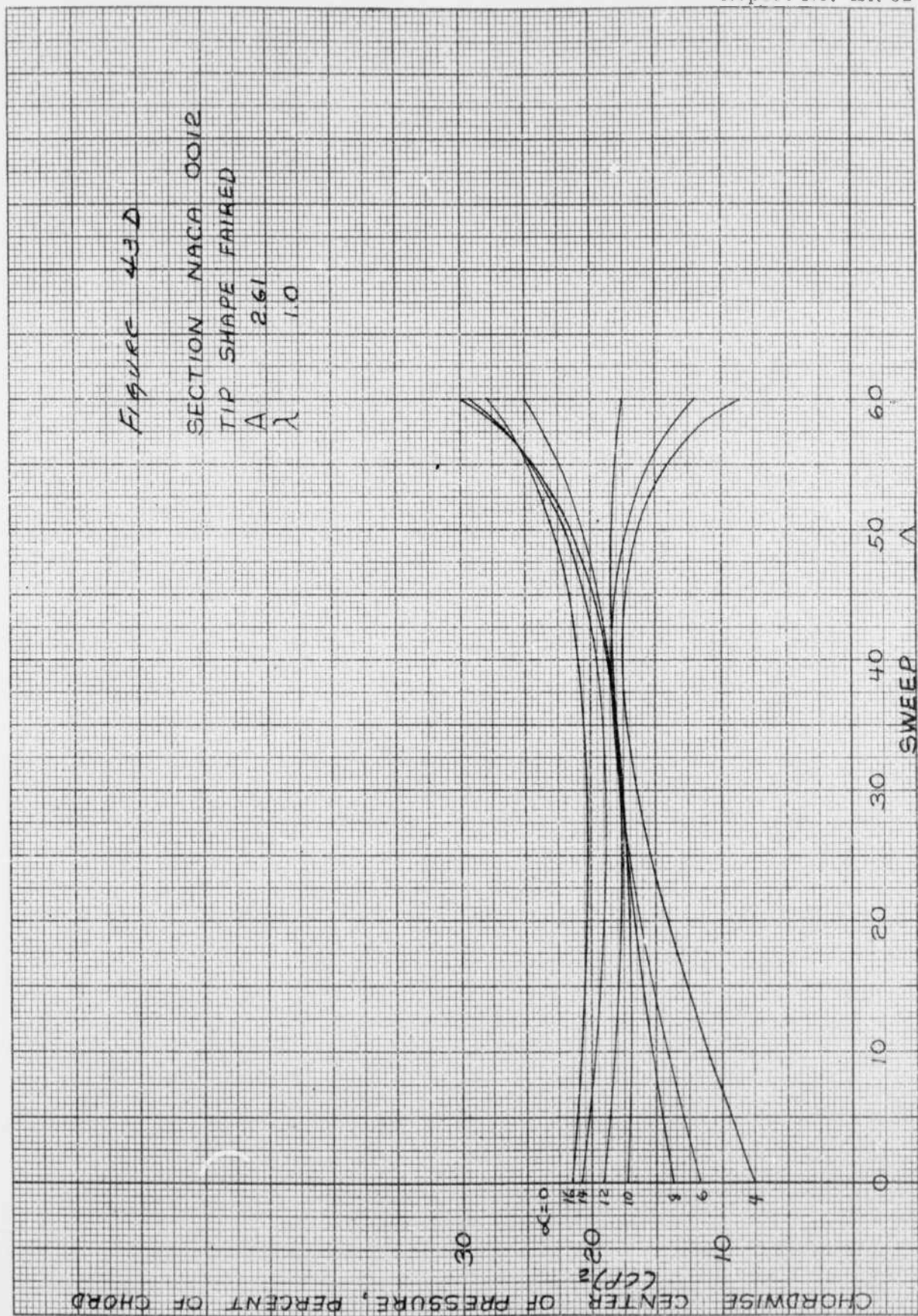


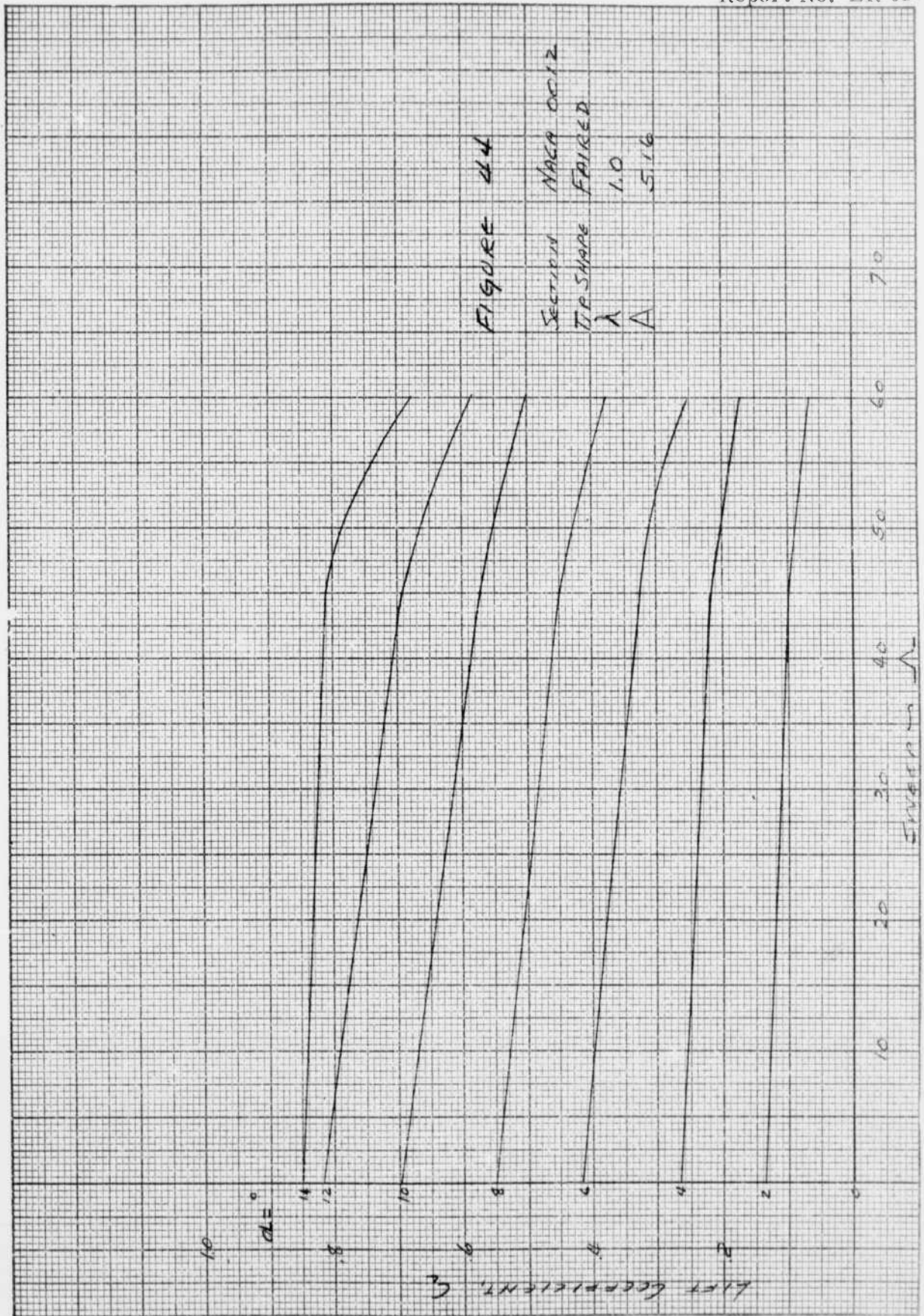


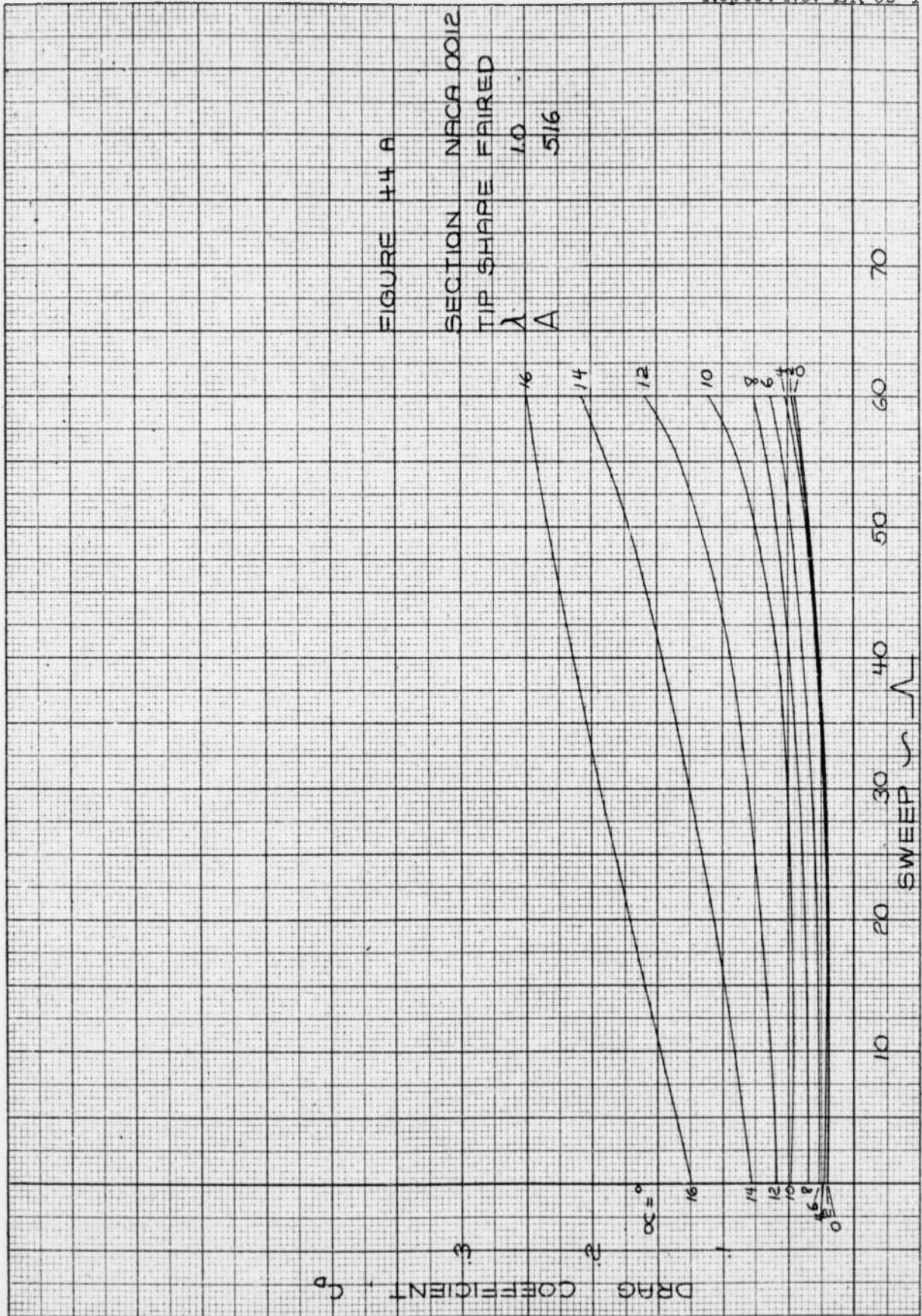


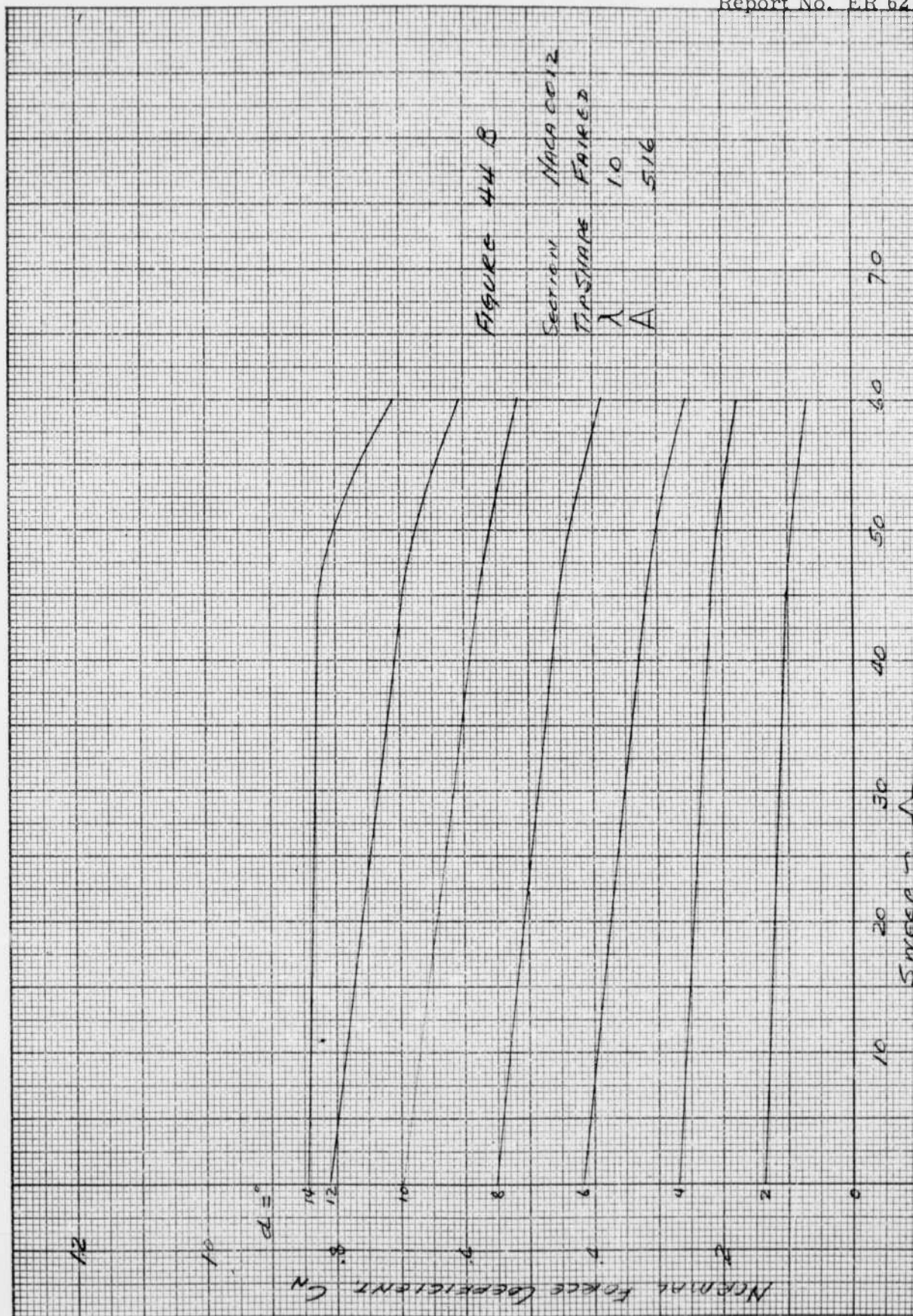


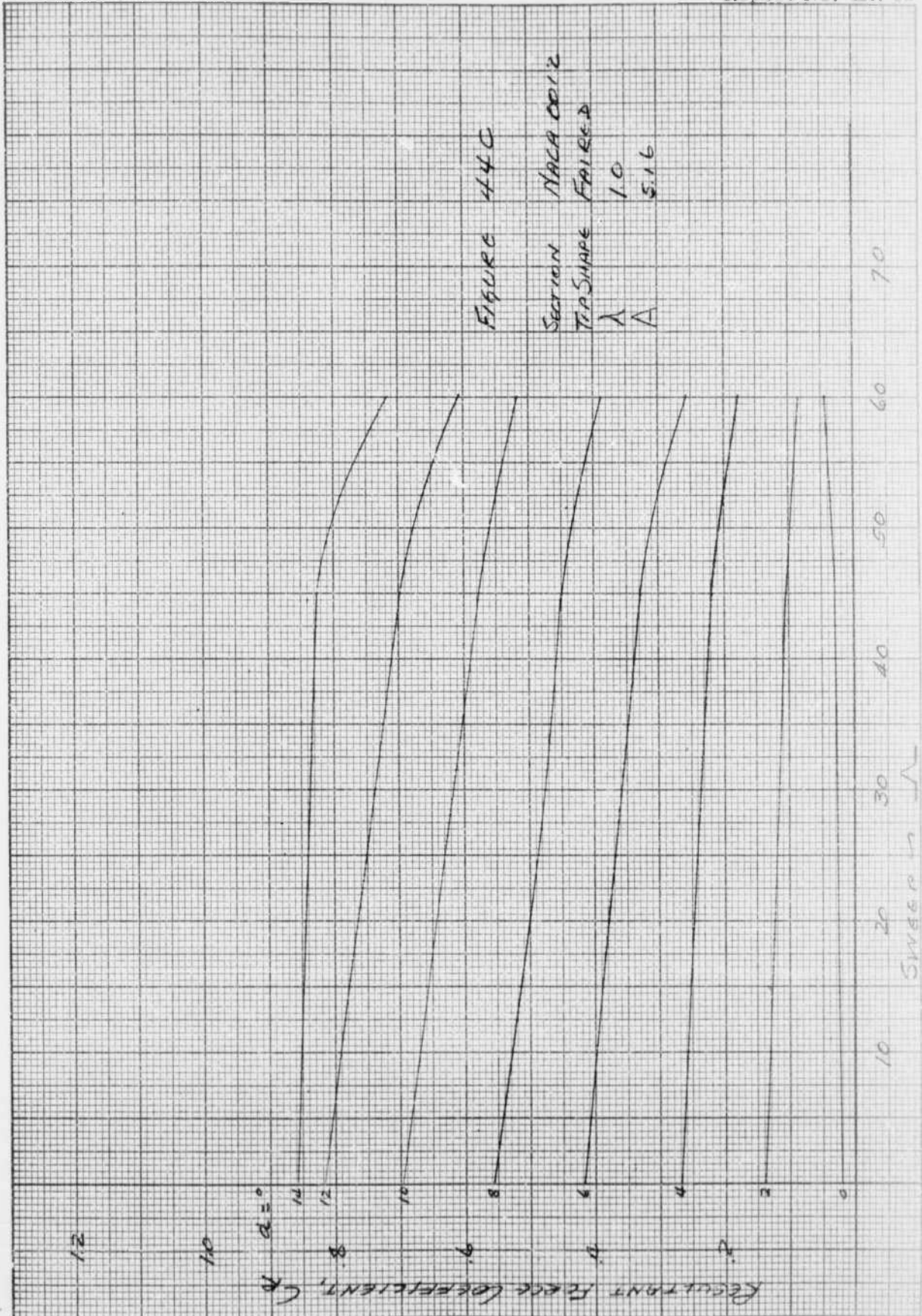


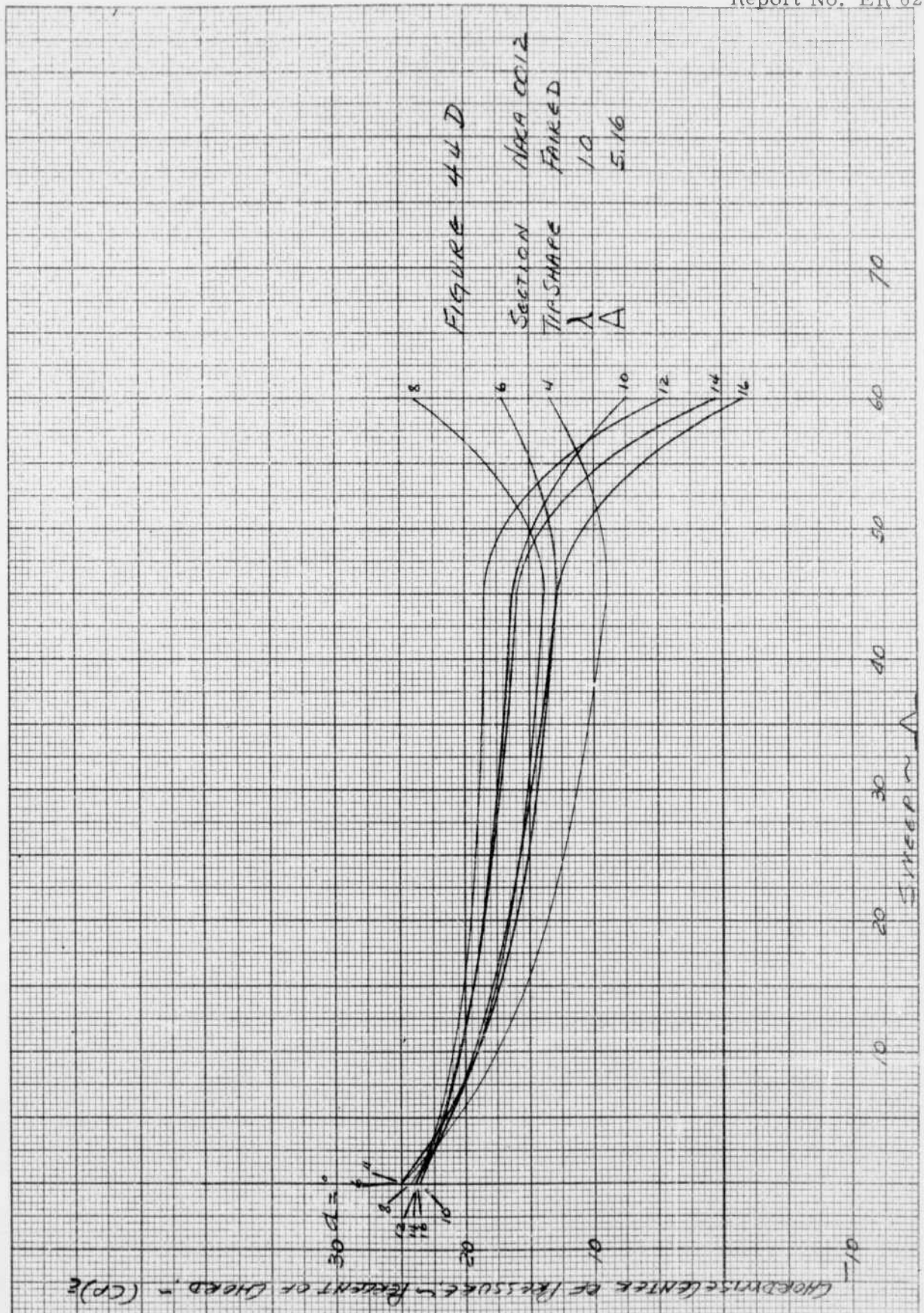


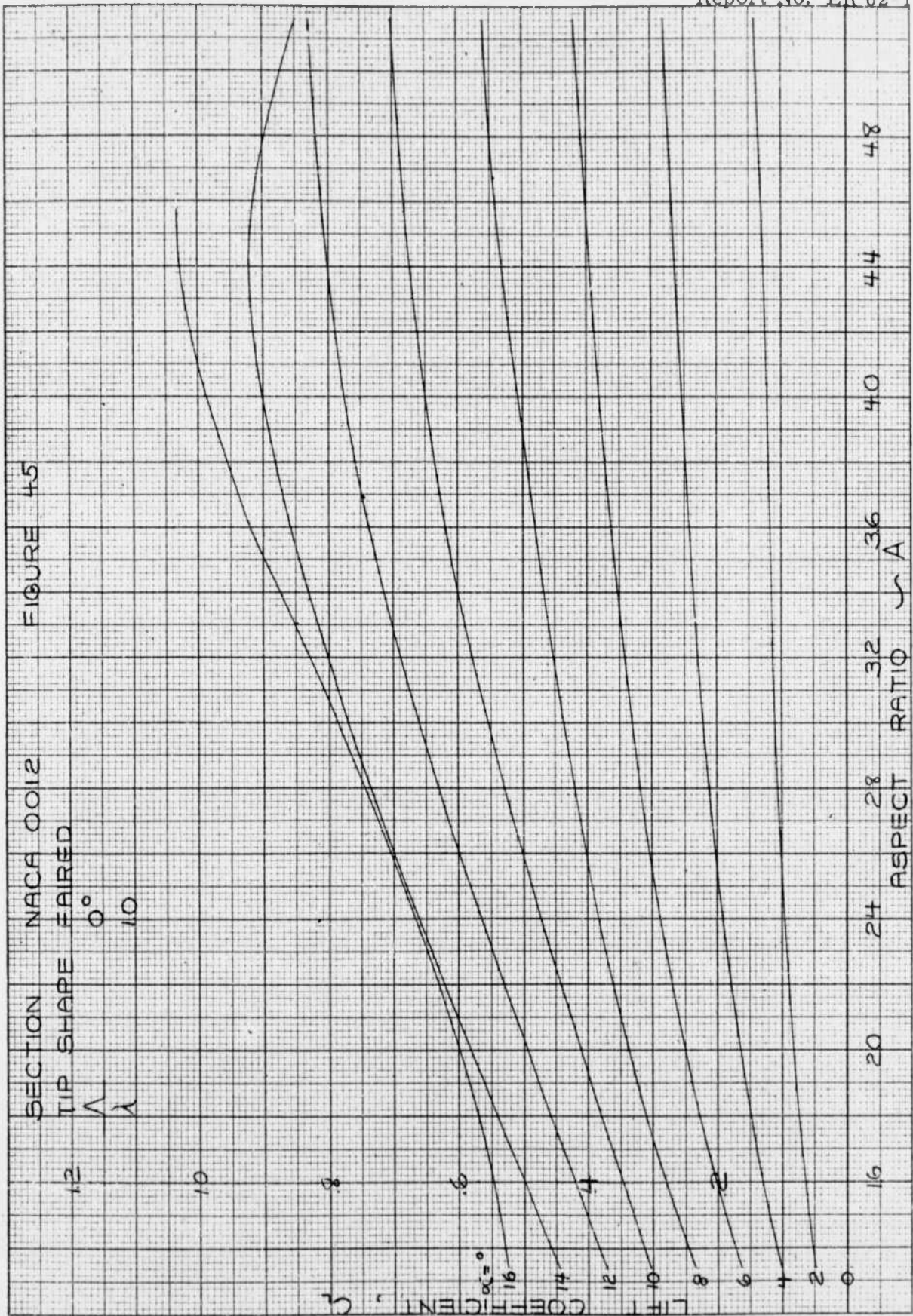


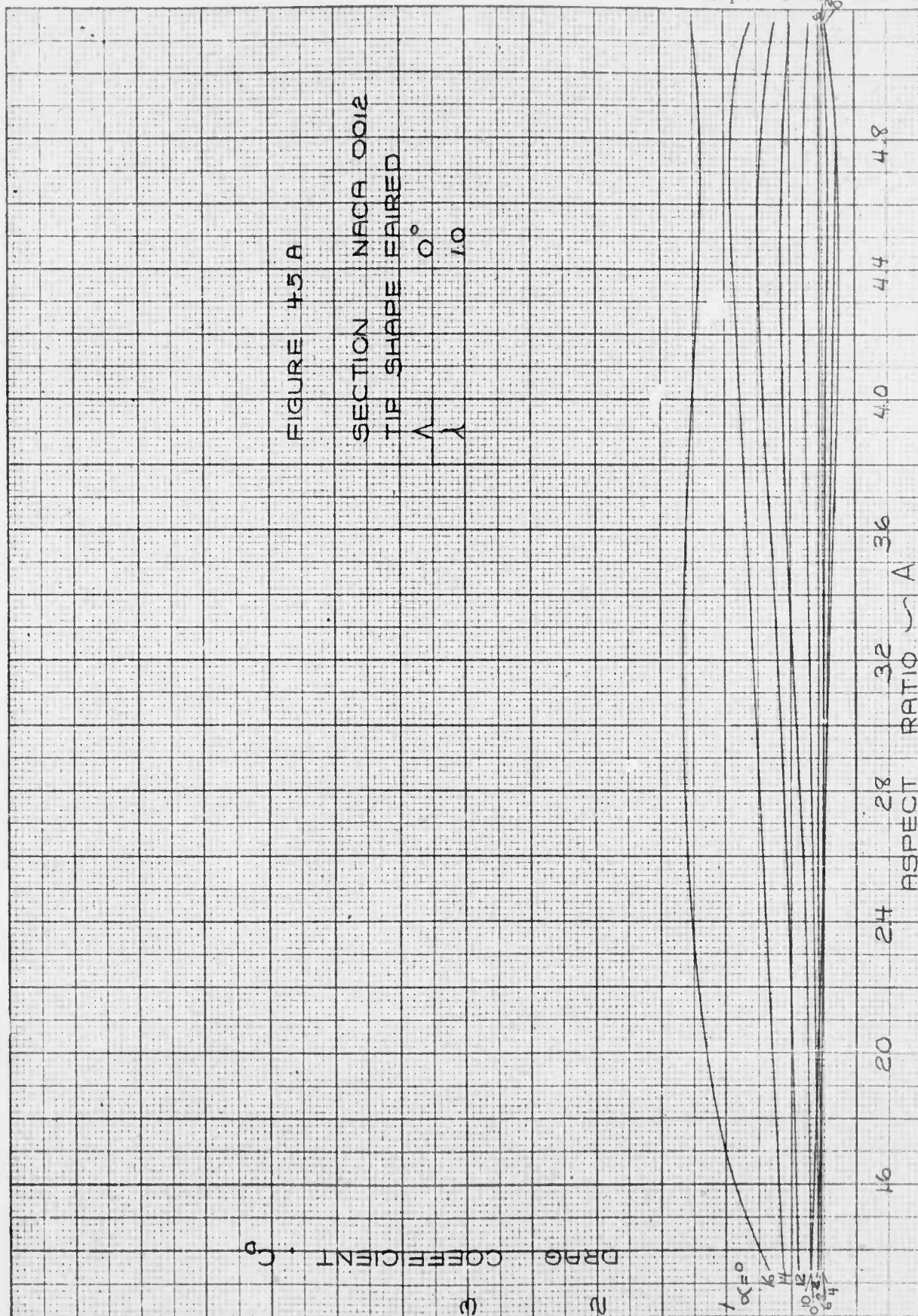


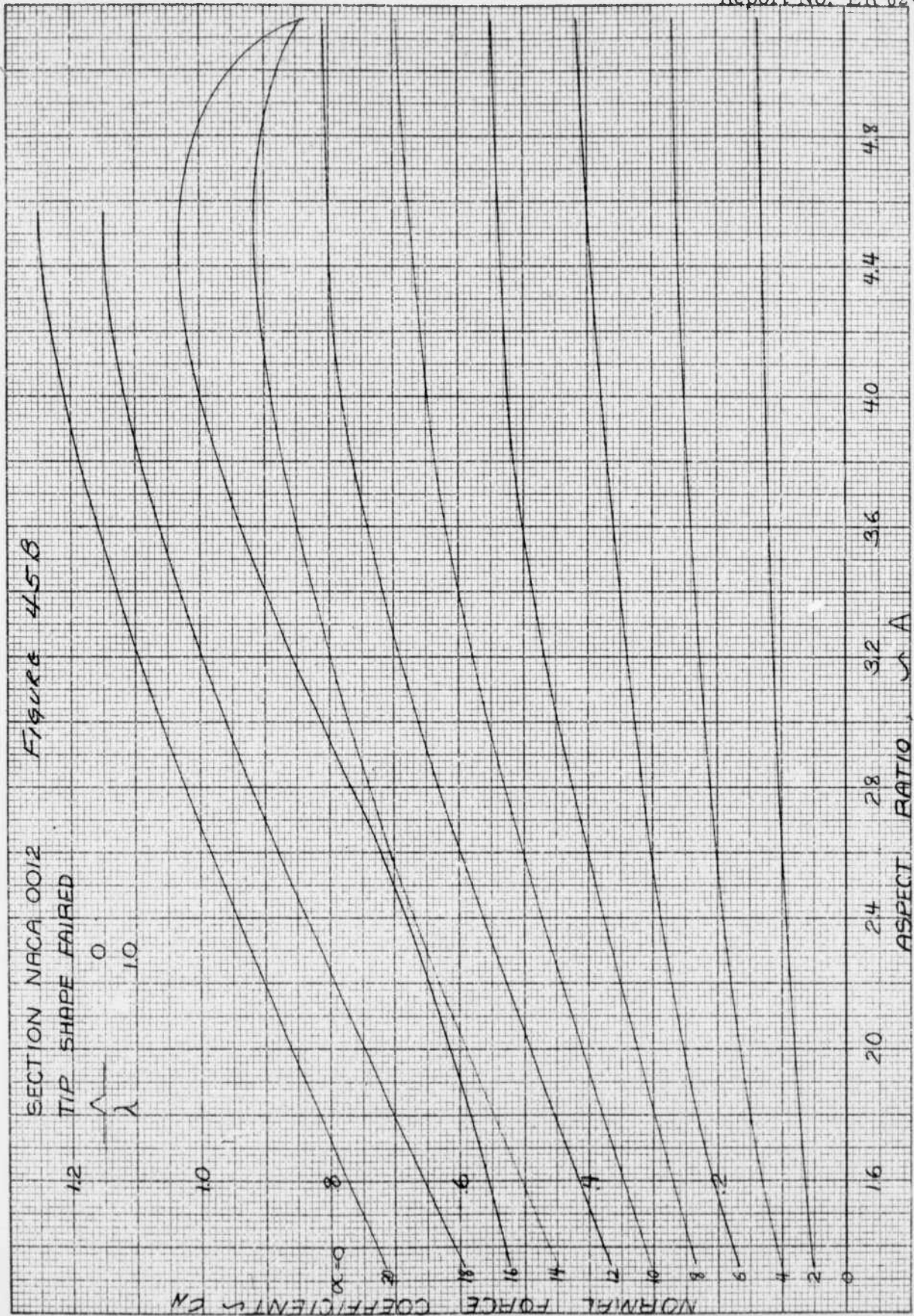


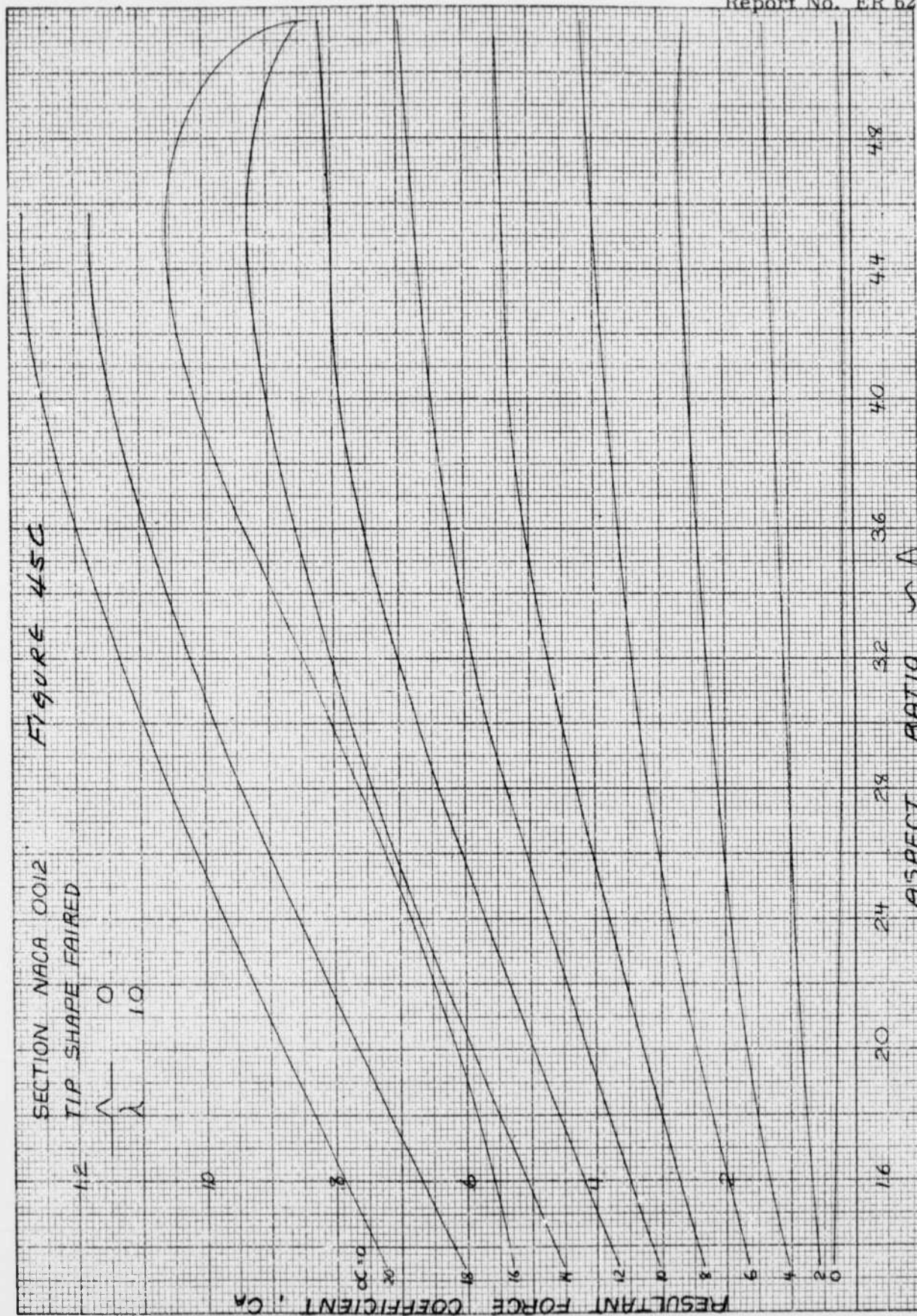


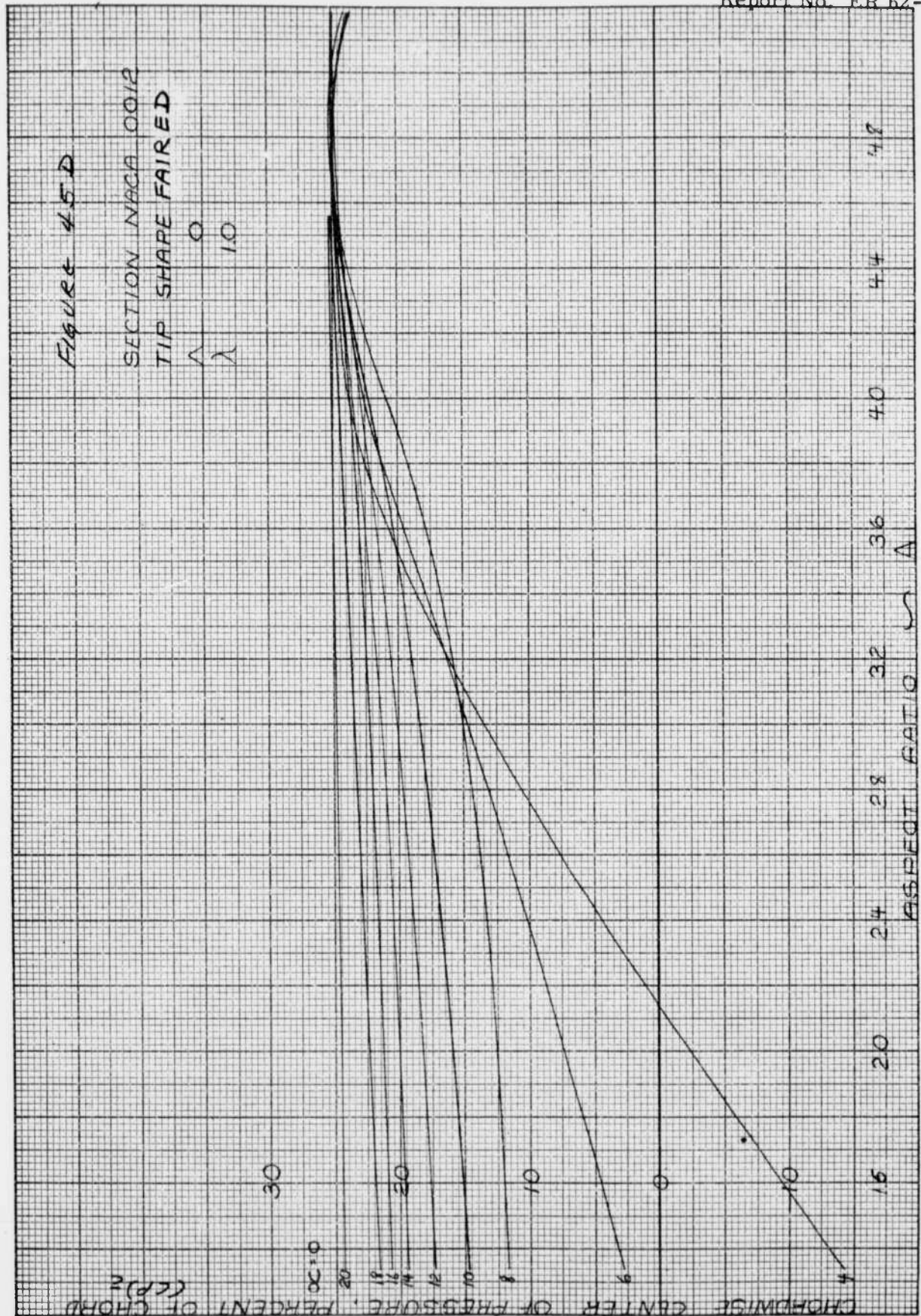


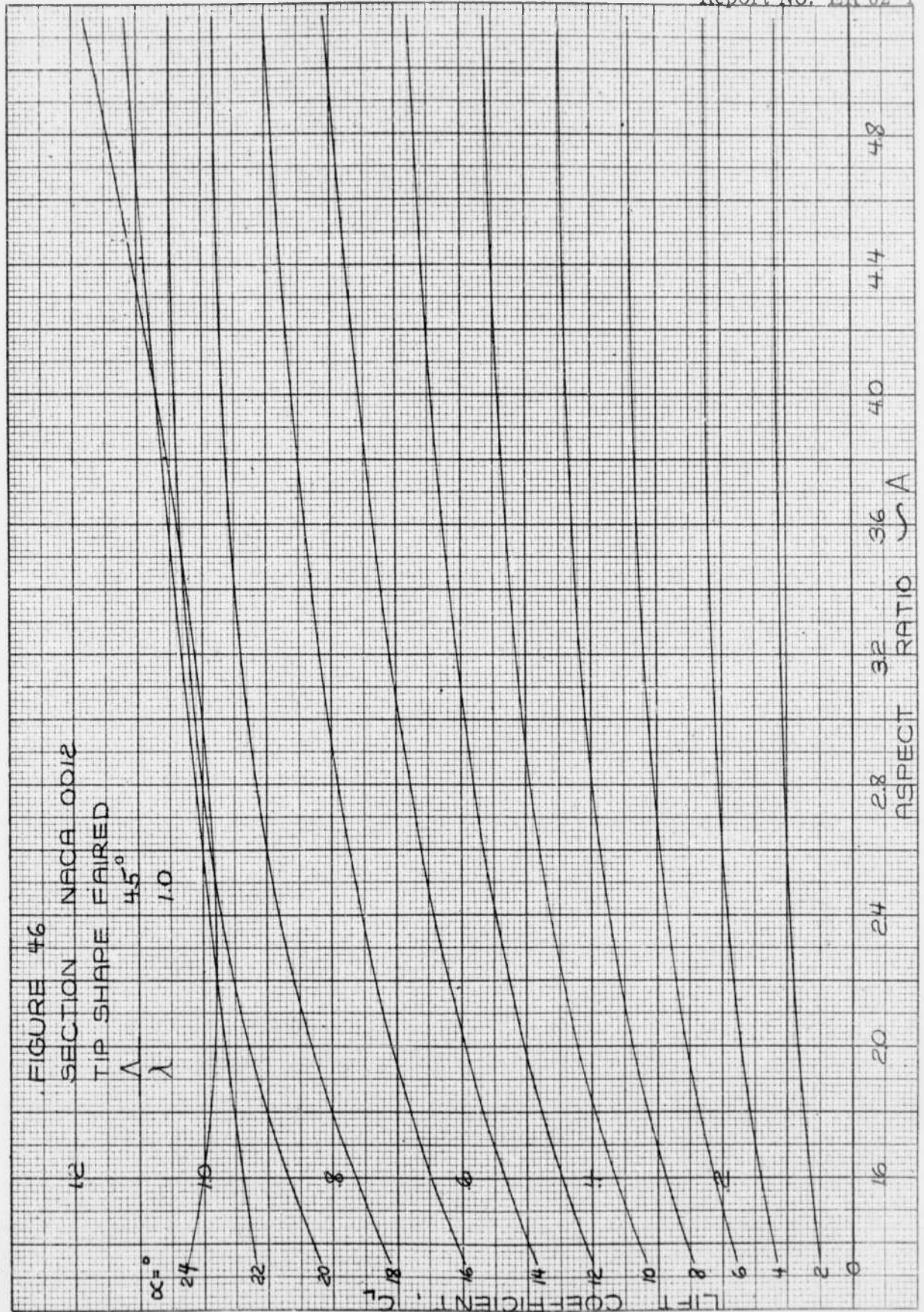


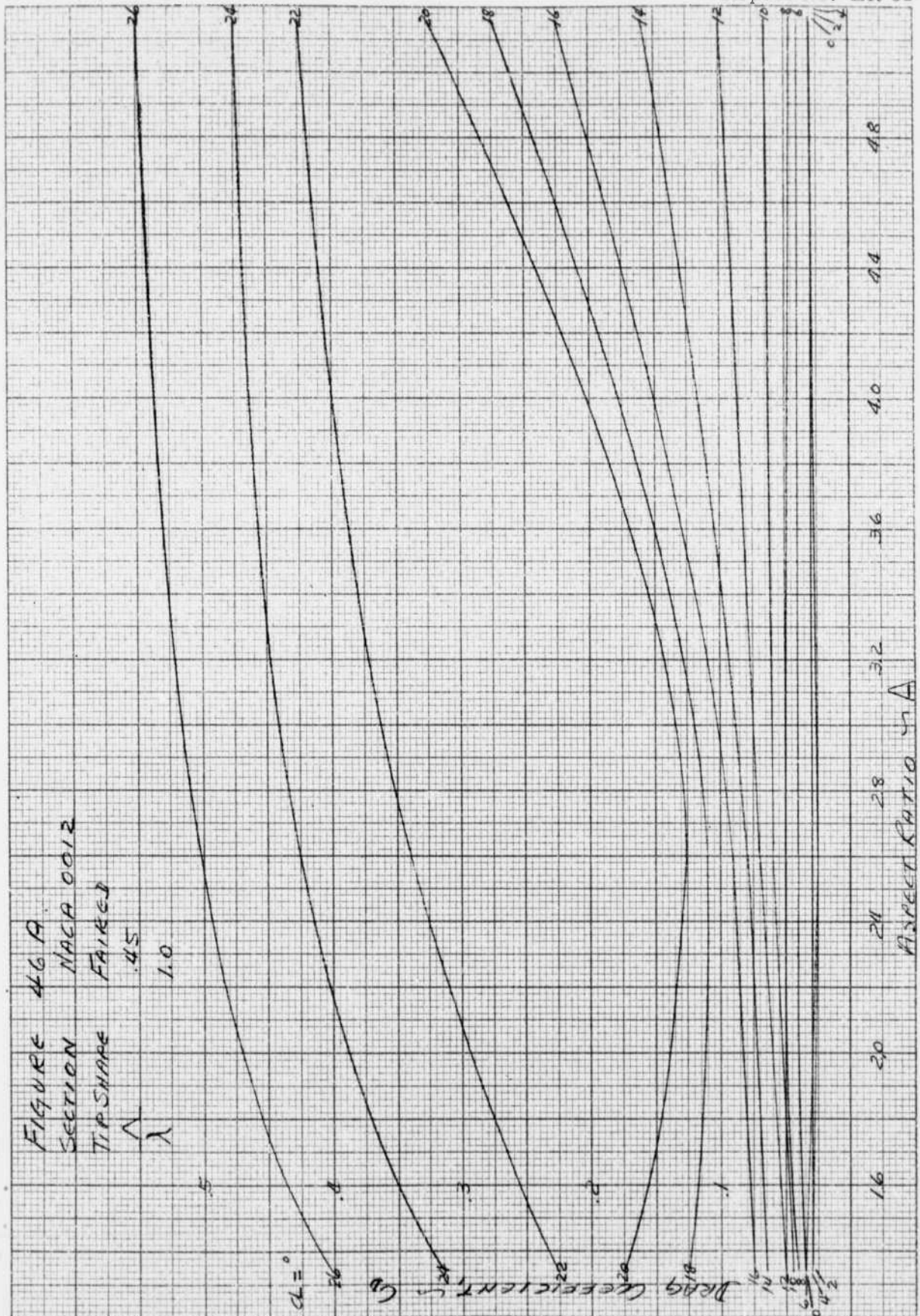


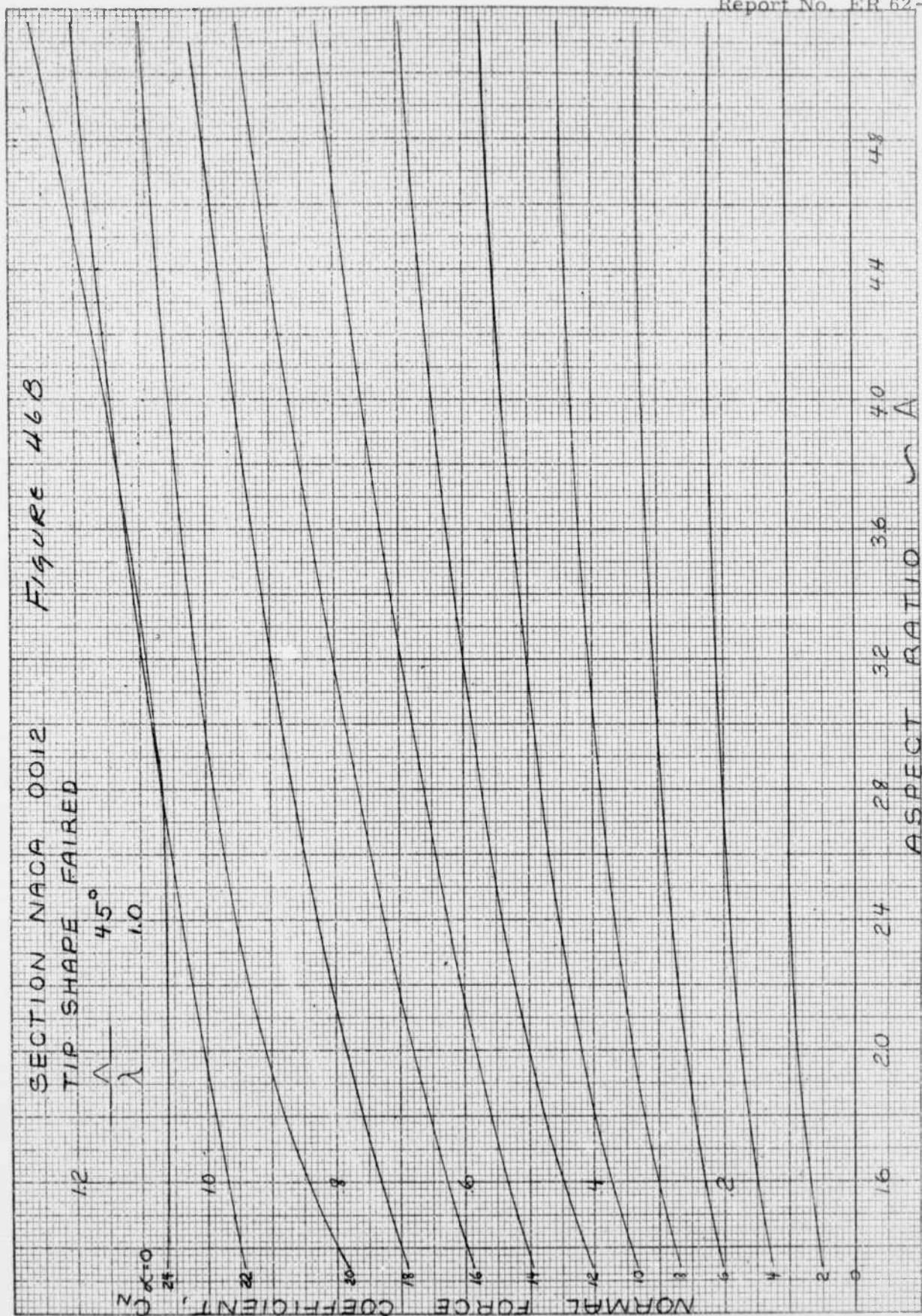


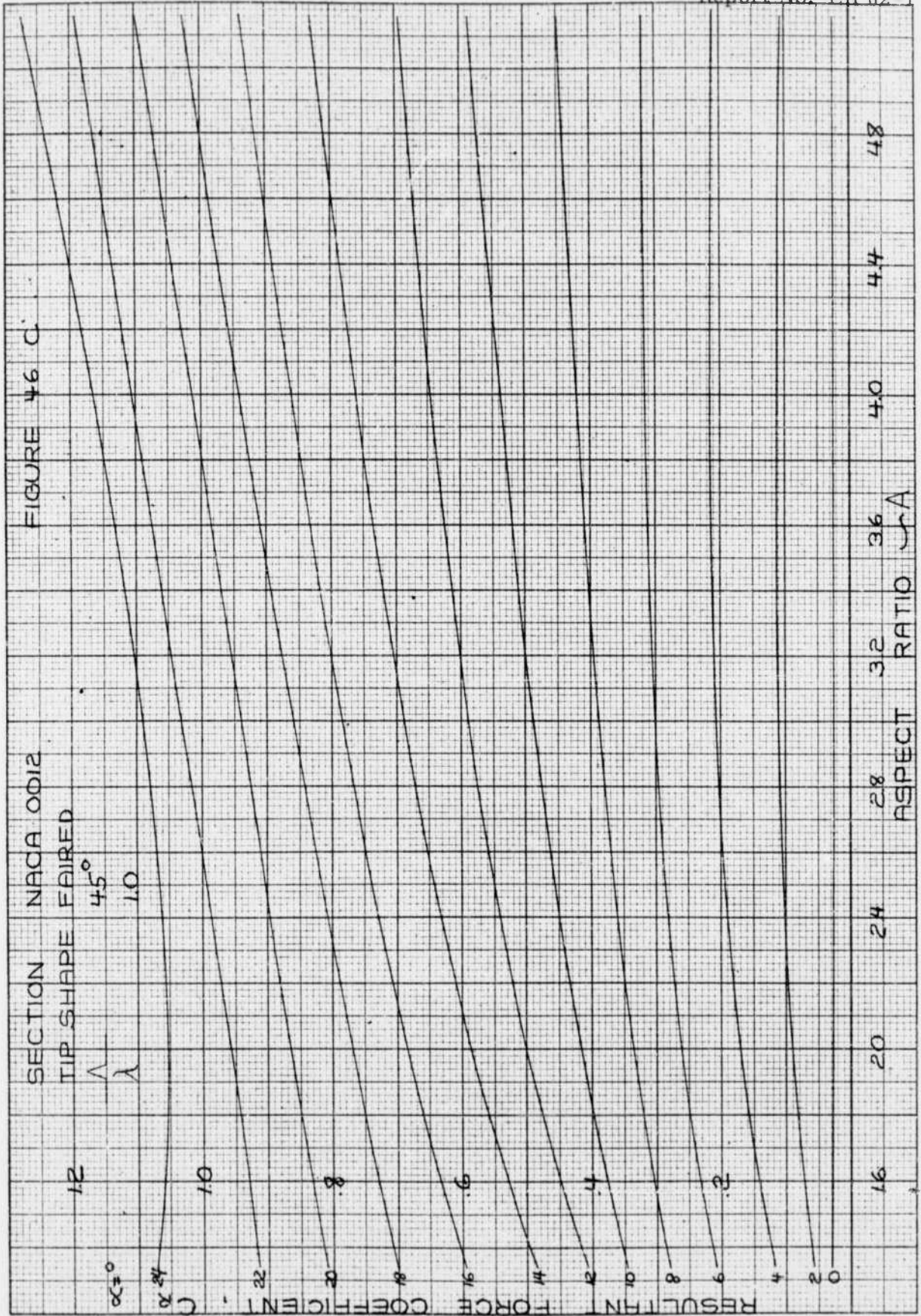


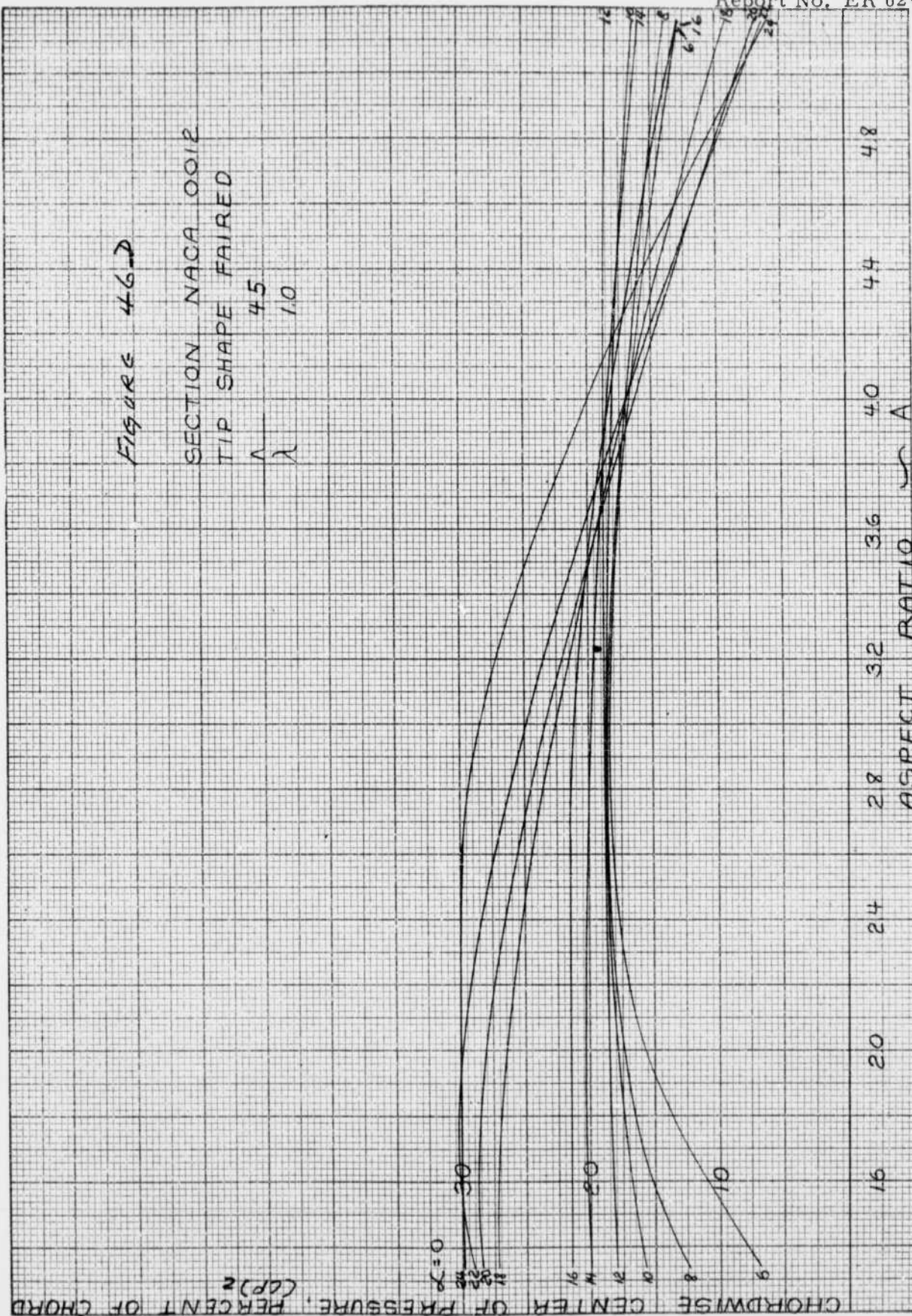


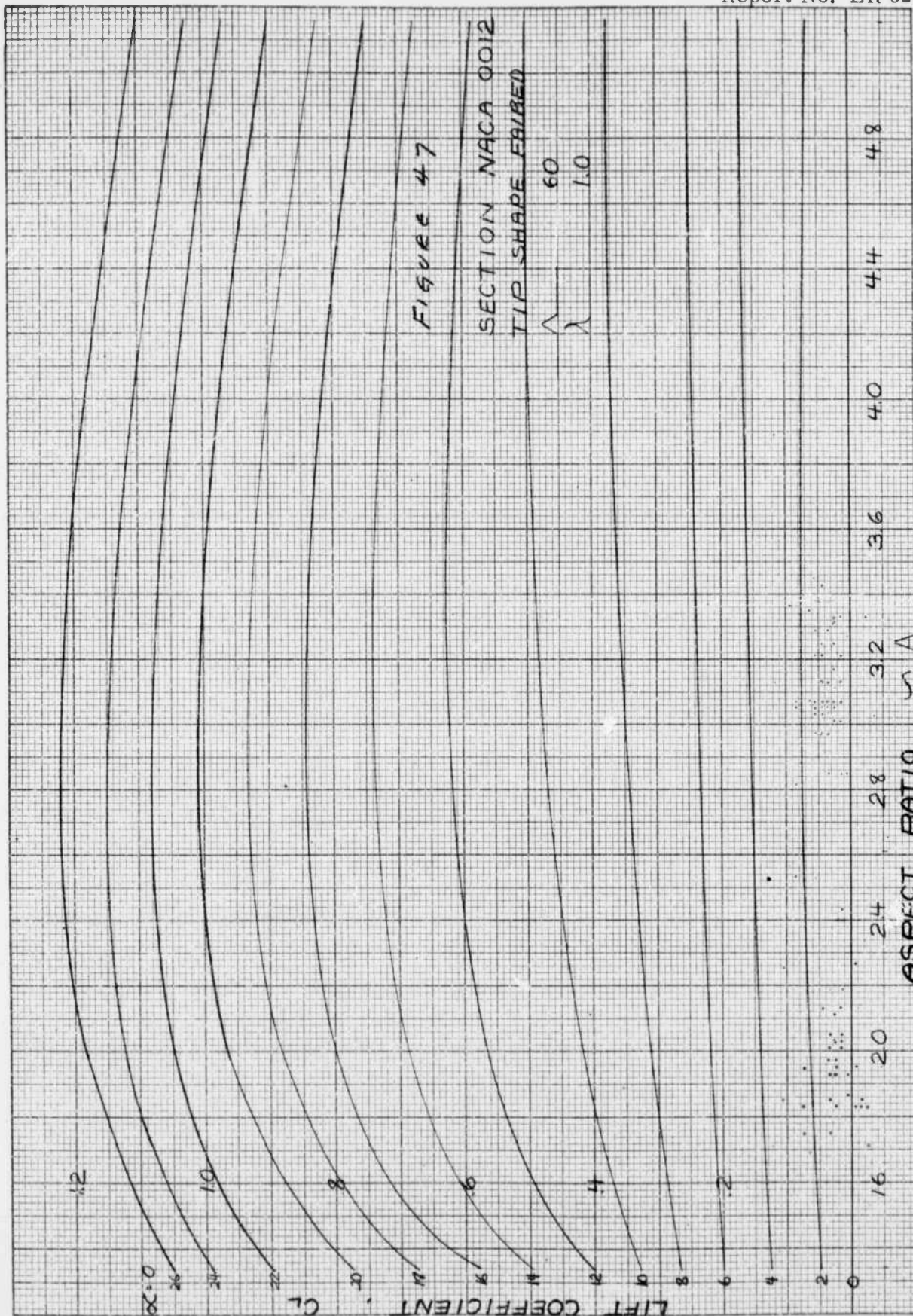


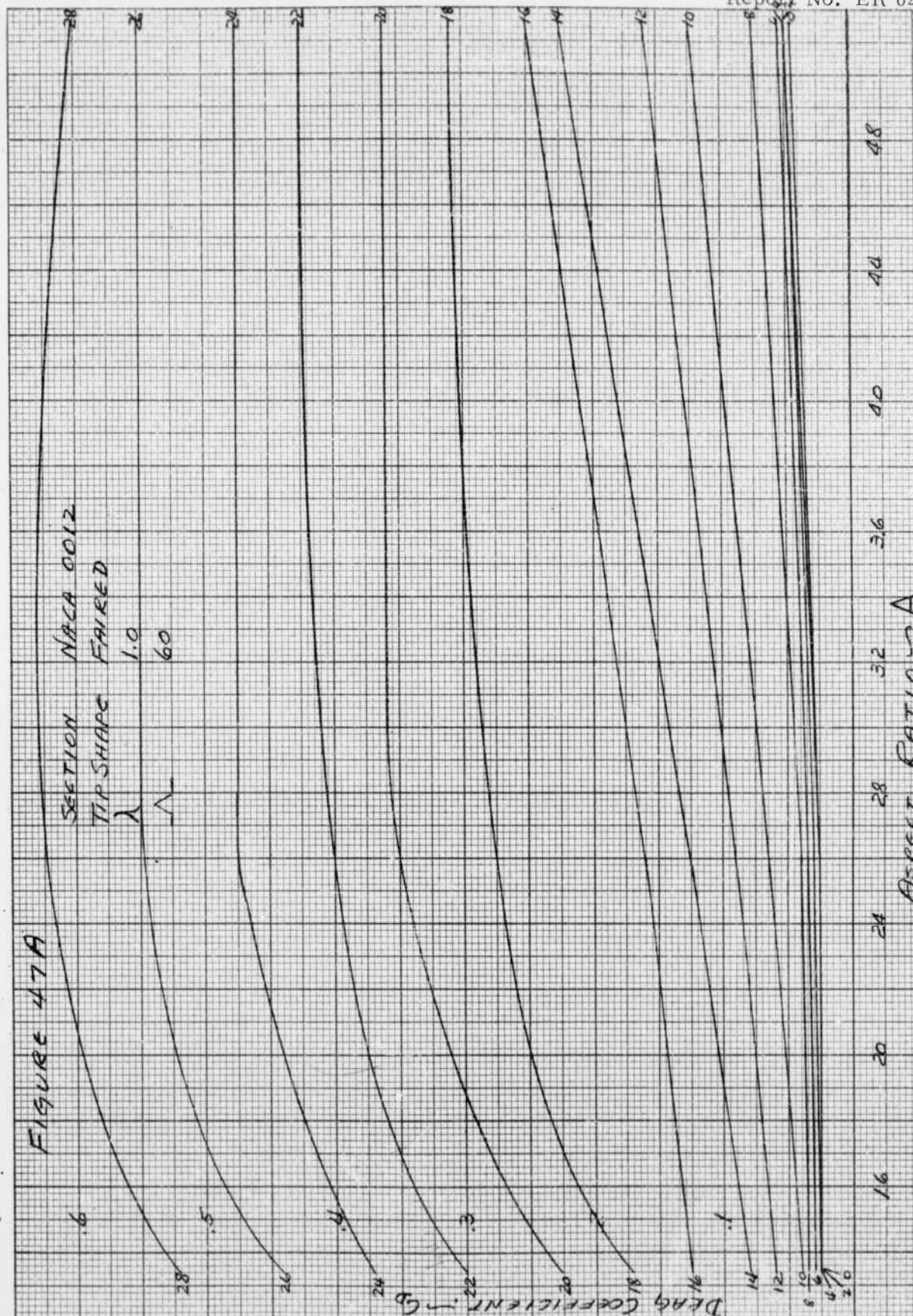


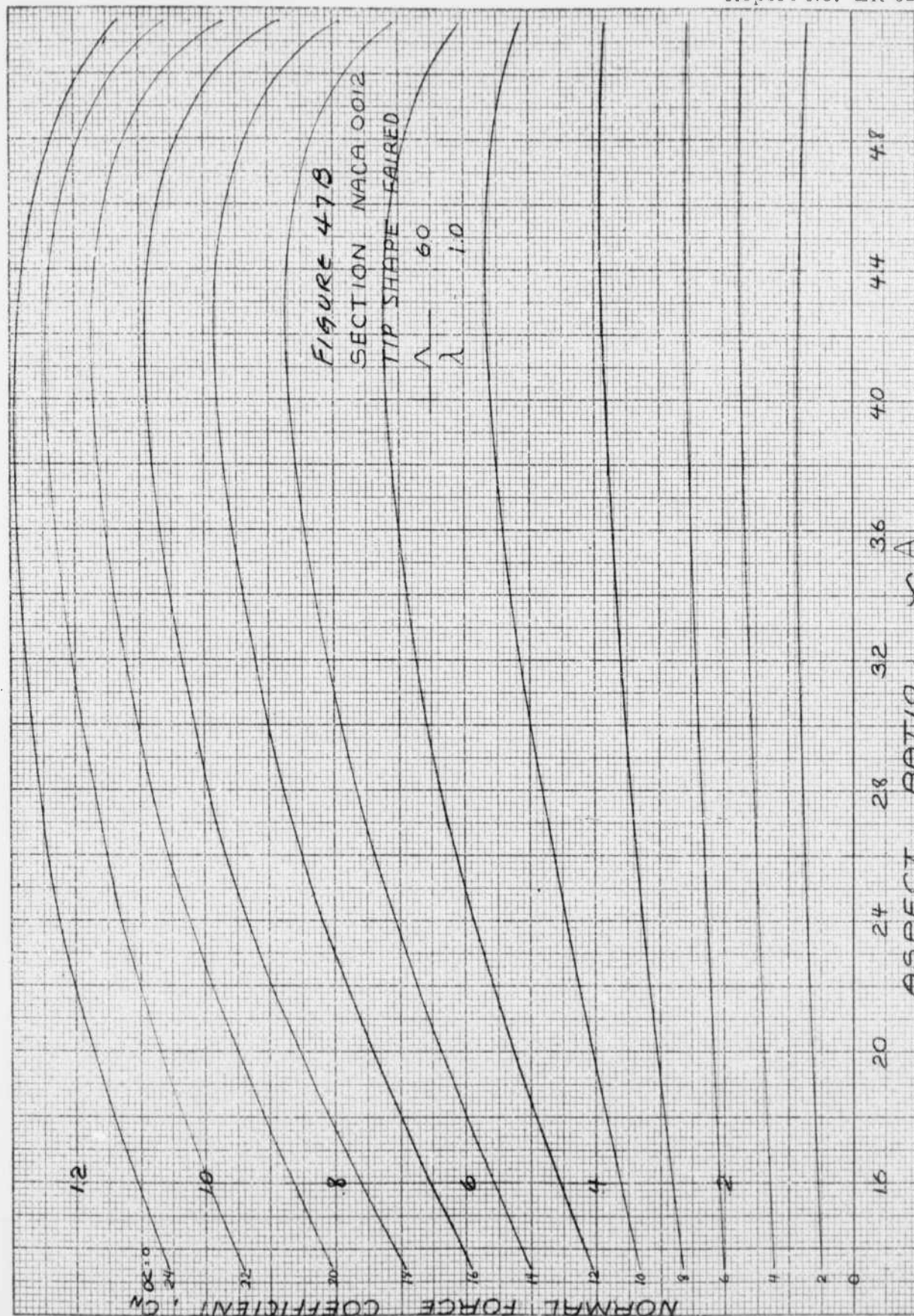


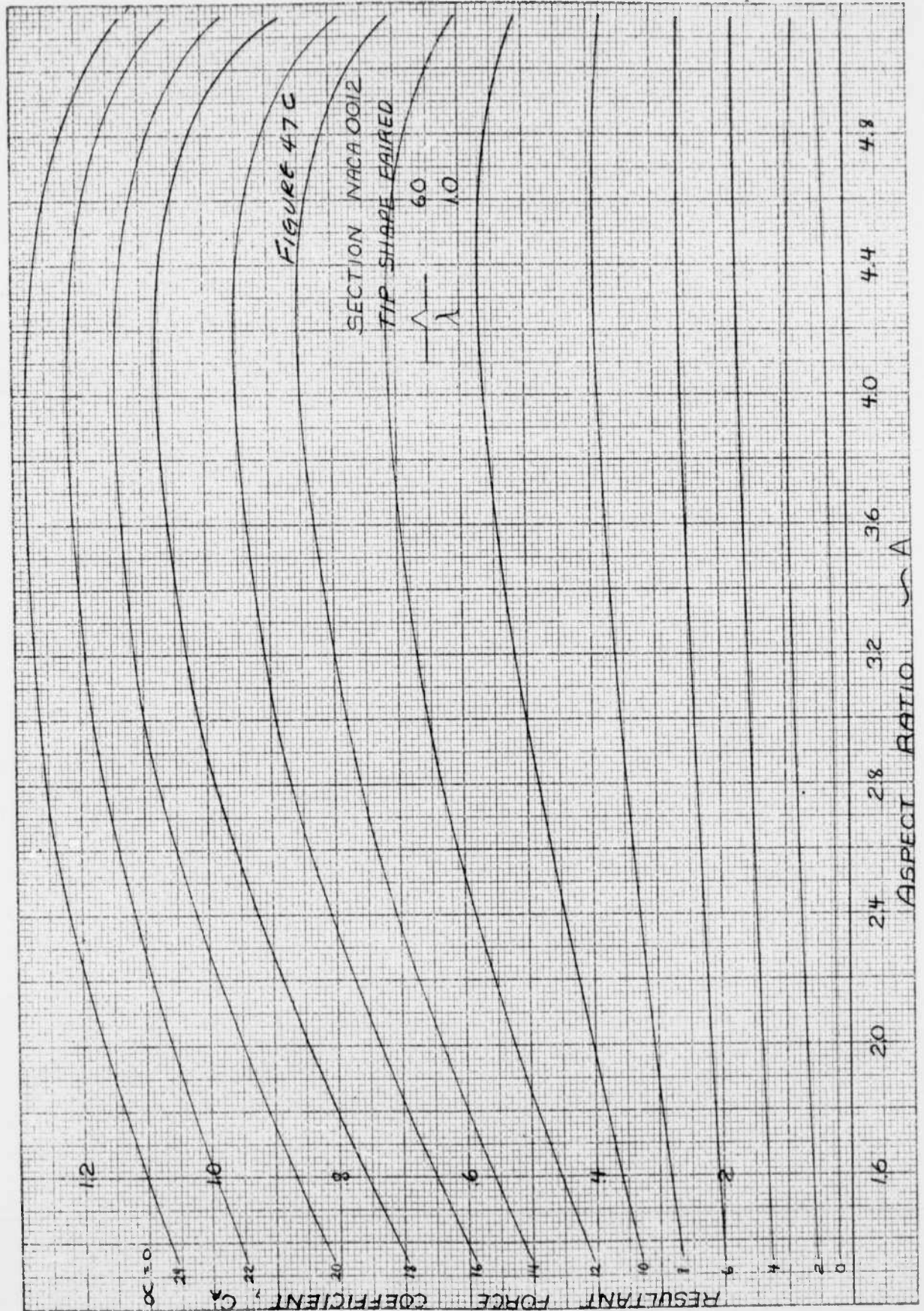


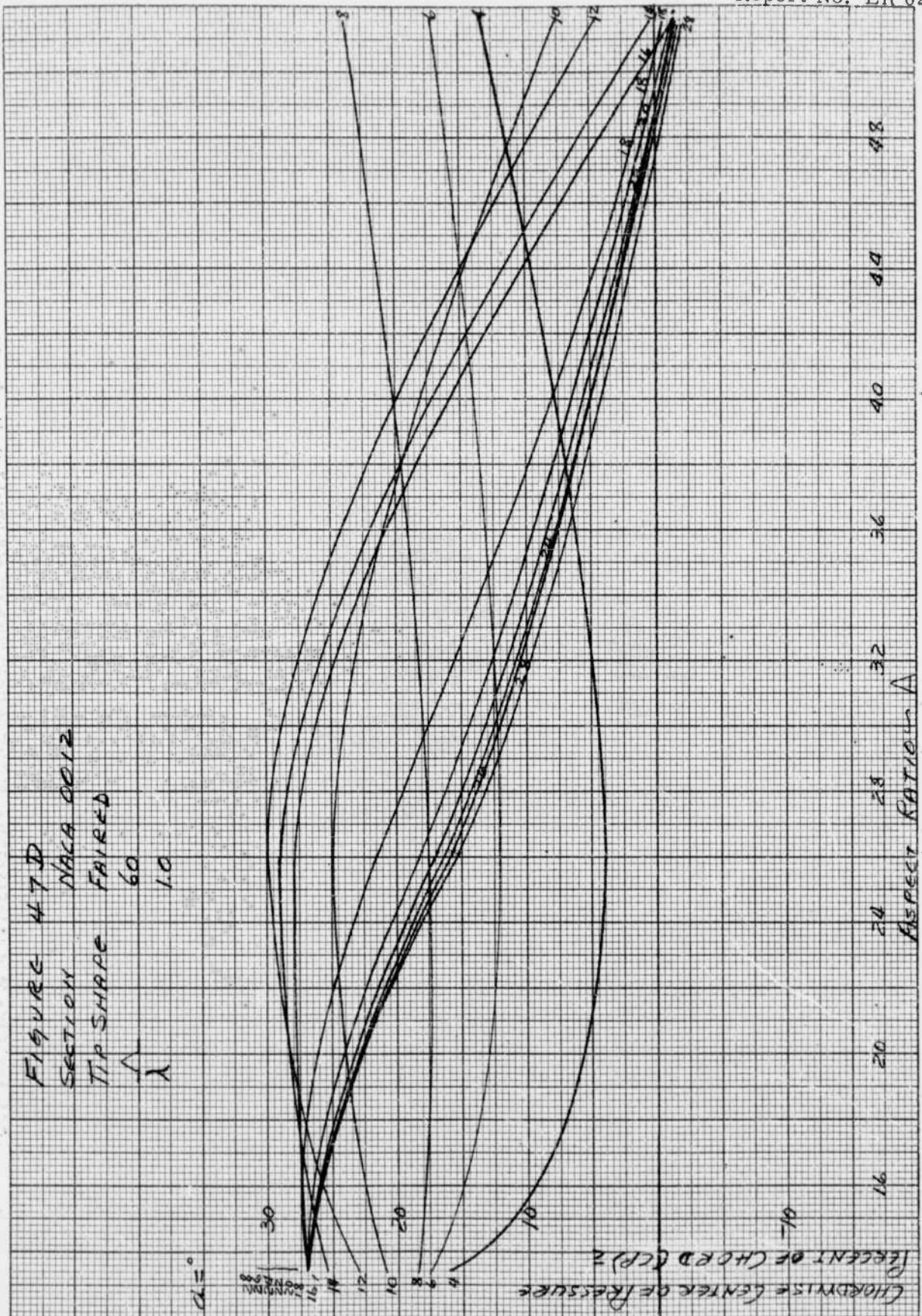


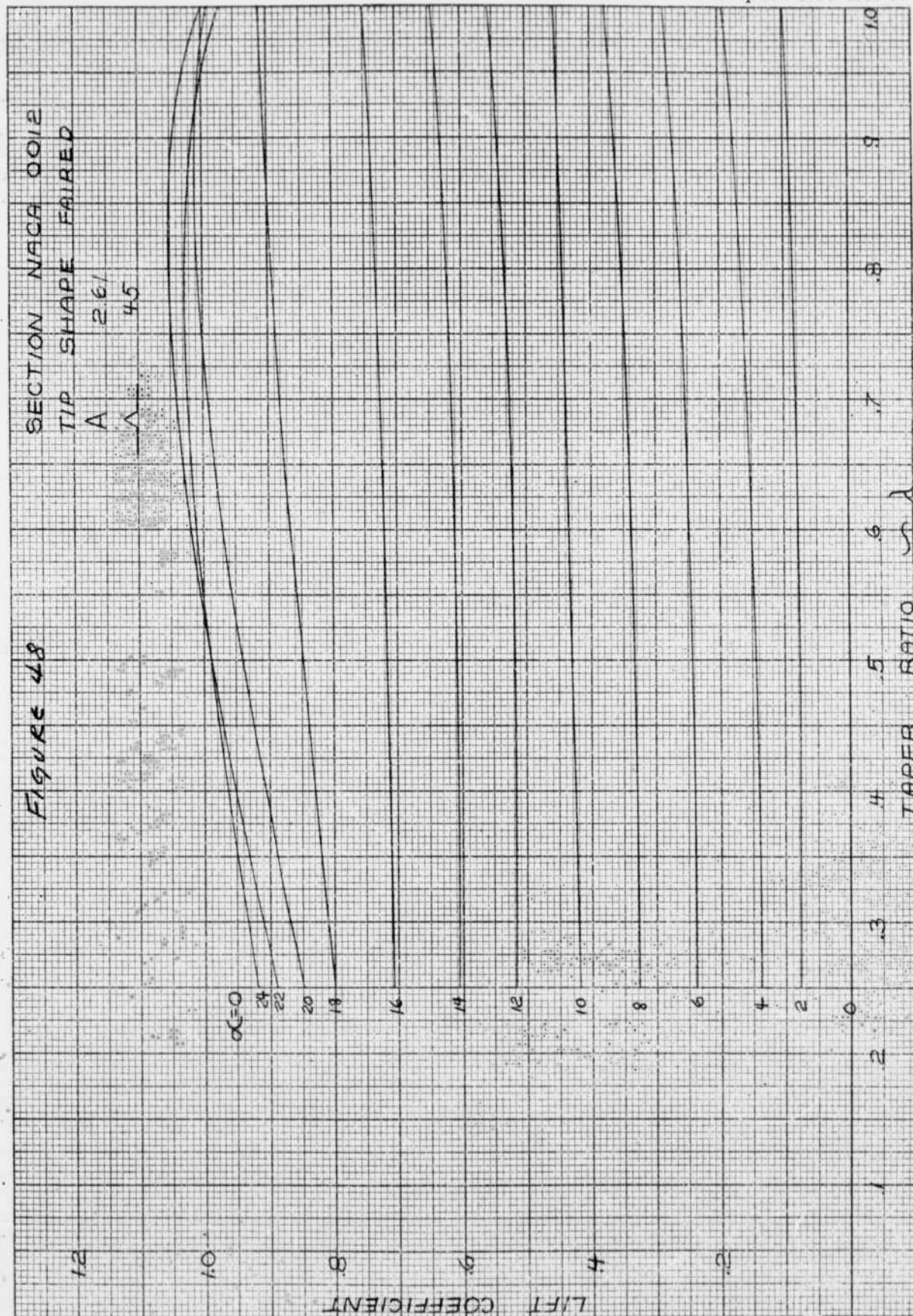


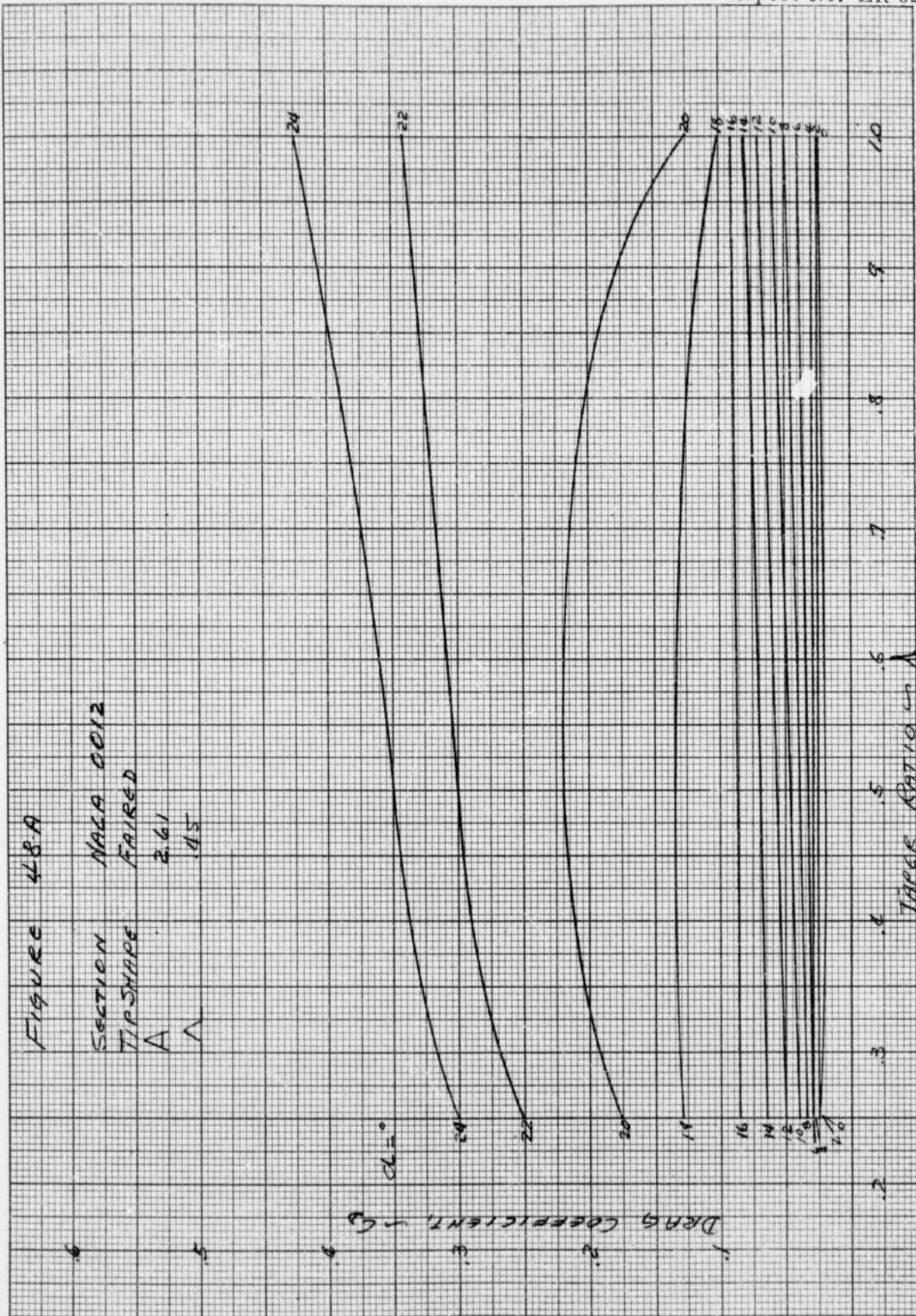


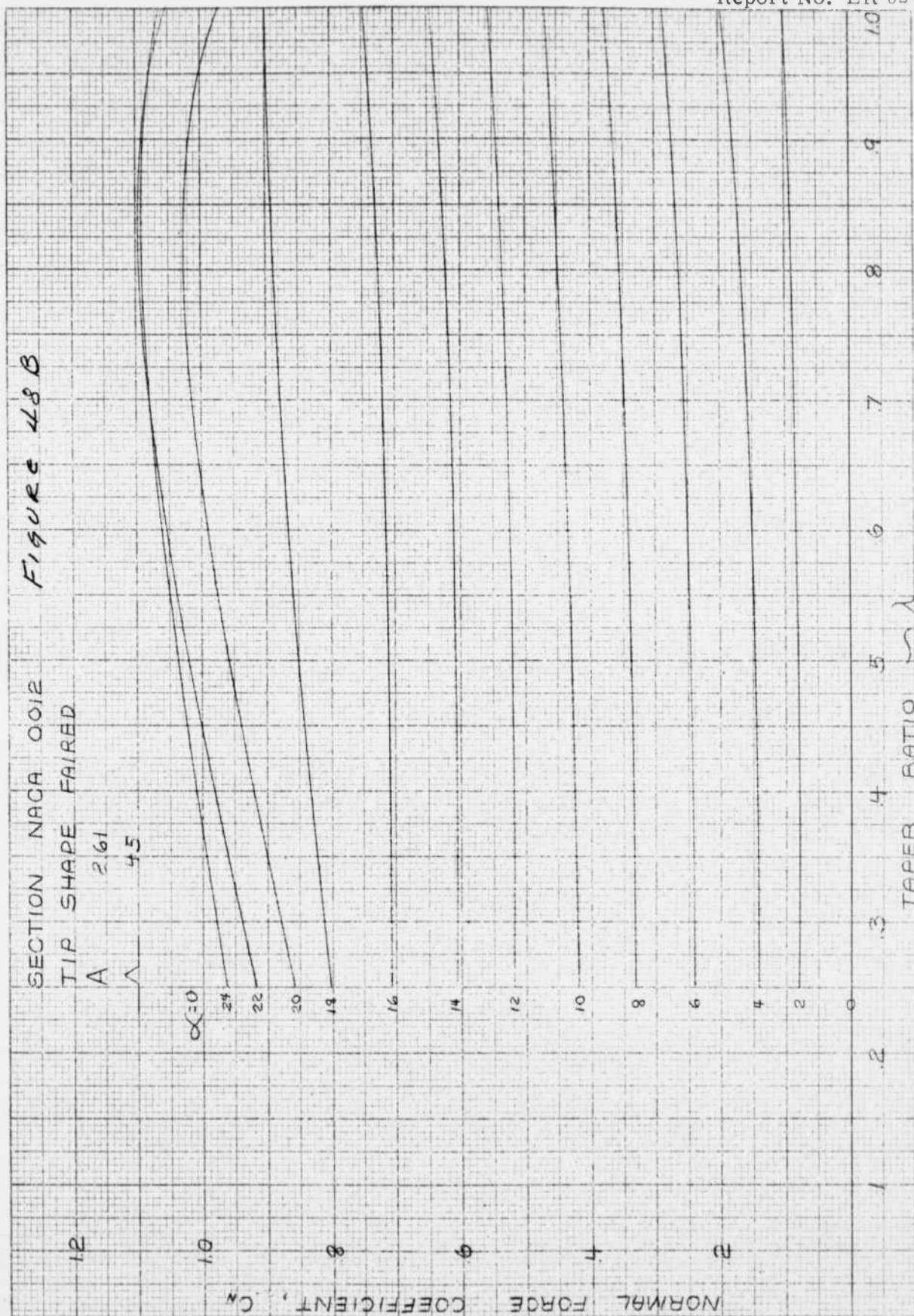


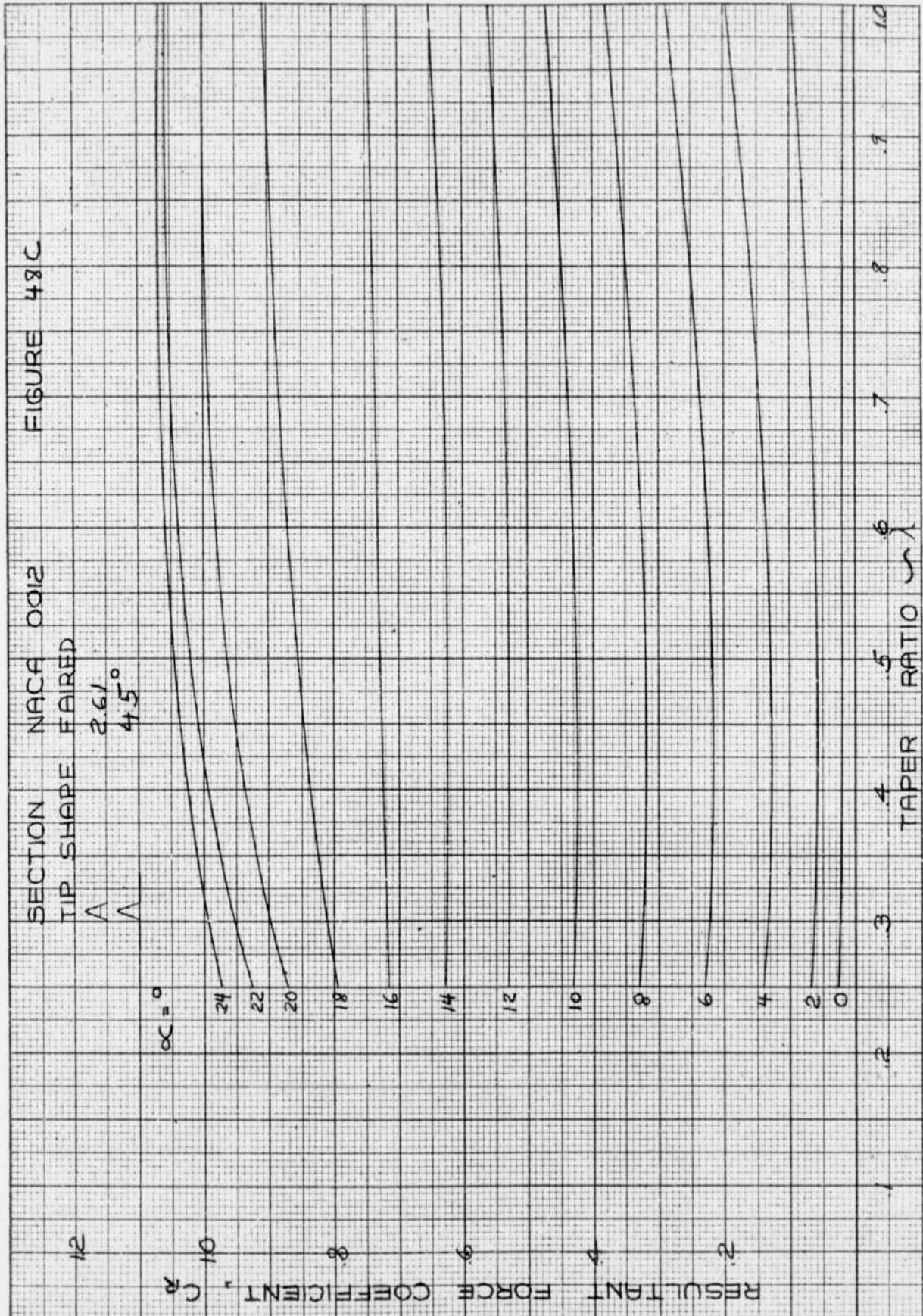












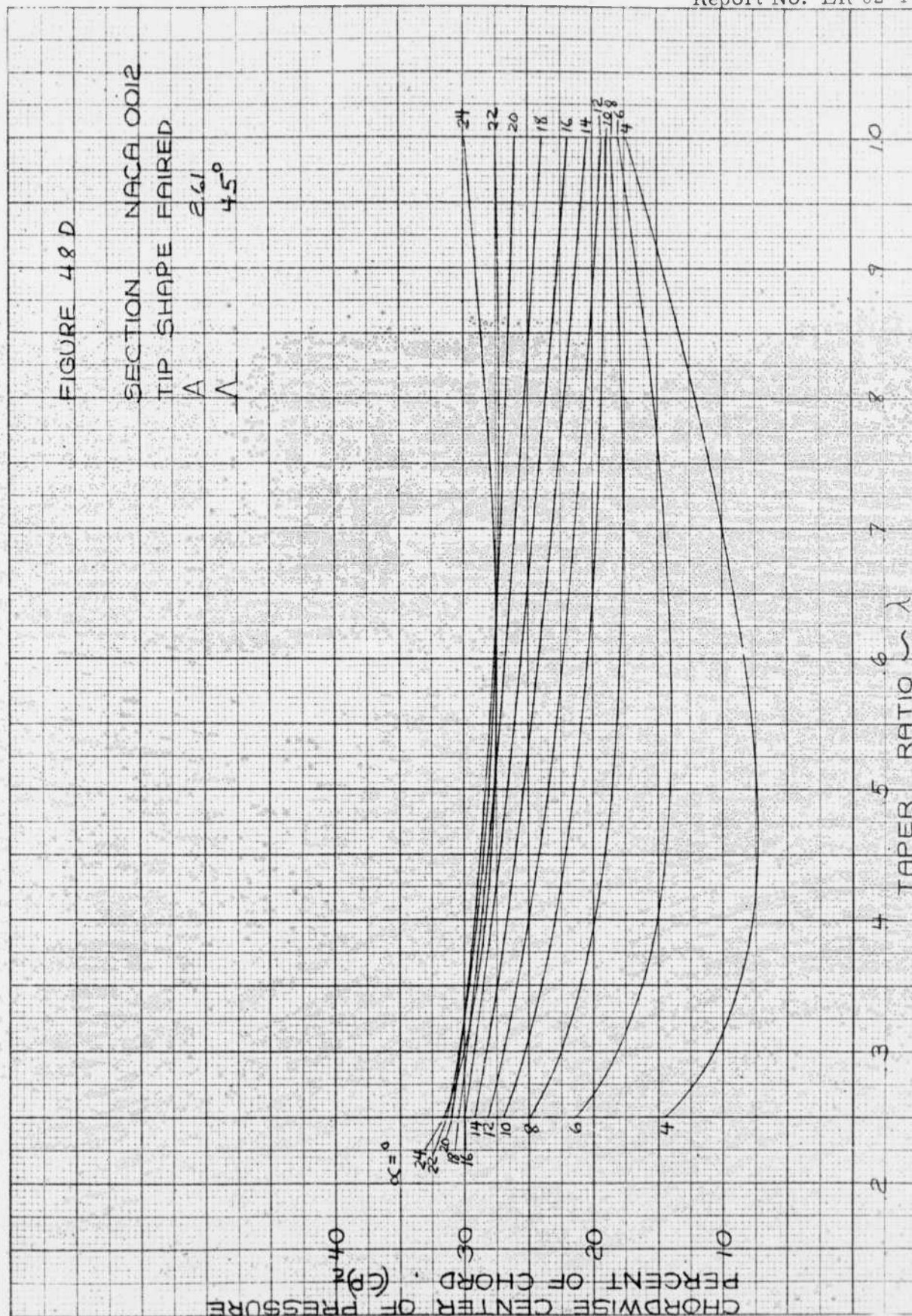


FIGURE 42

SECTION NACA 64AD10
TIP SHAPE FAIRED

λ 0°
 λ 1.0

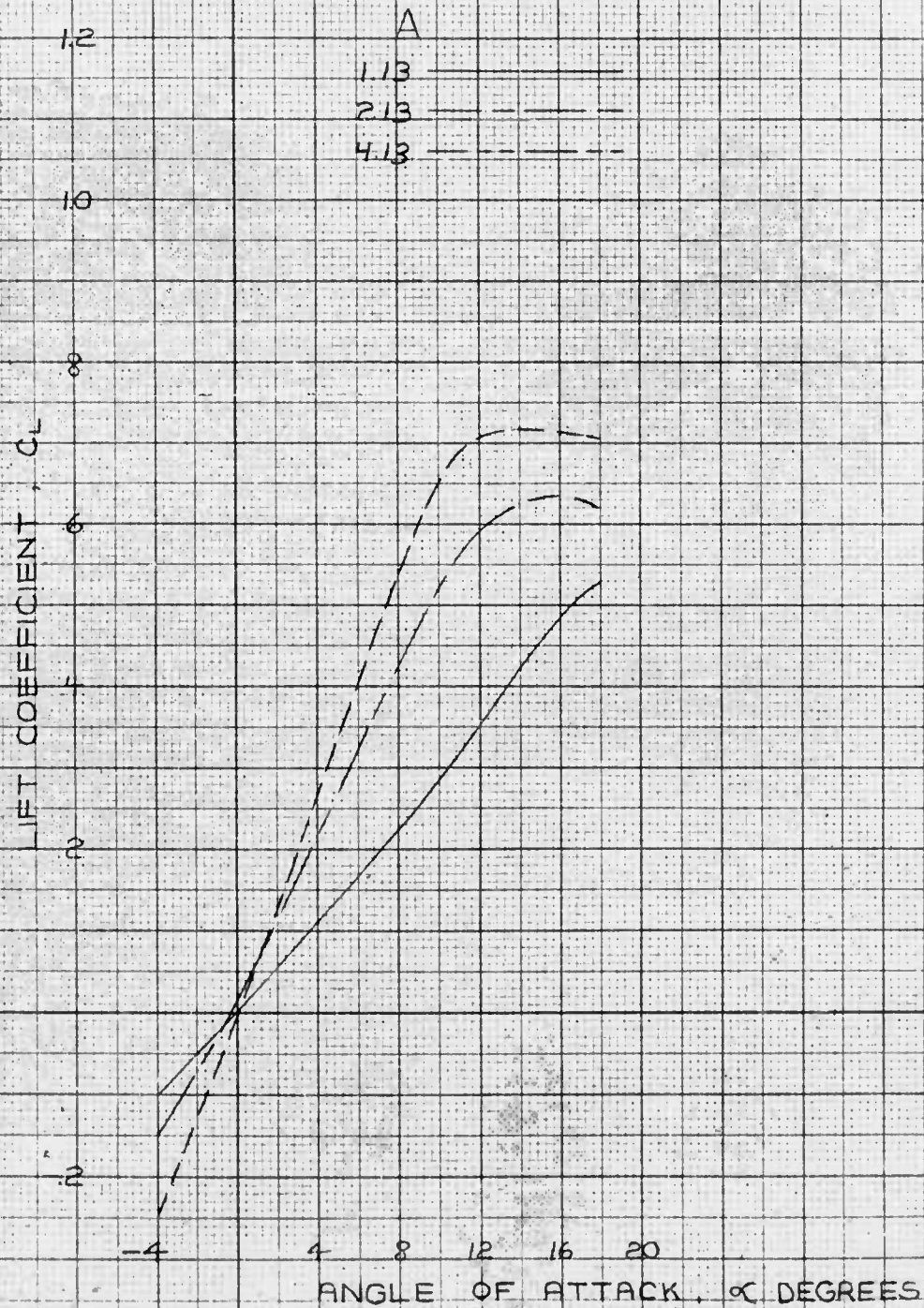


FIGURE 49A

SECTION NACA 64A010

TIP SHAPE FAIRED

Λ C°

λ 10

A

1.13 —————

2.13 —————

4.13 - - - - -

DRAG COEFFICIENT, C_D

ANGLE OF ATTACK, α DEGREES

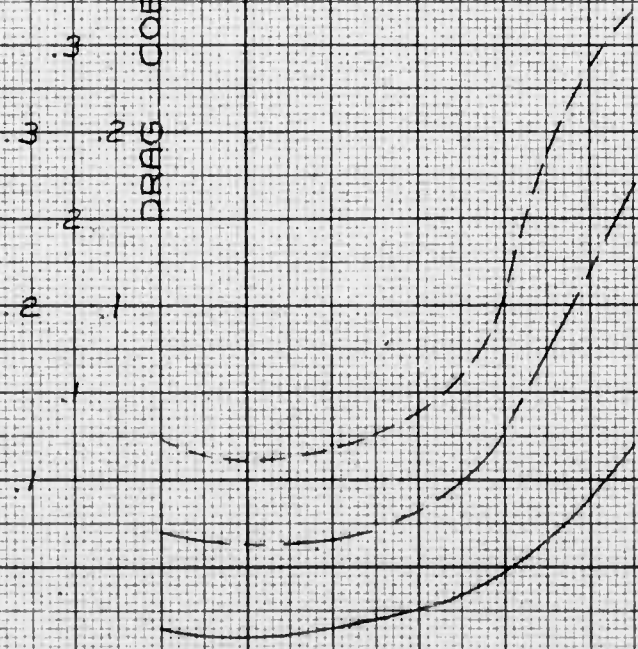


Figure 49 B

SECTION NACA 64A010
TIP SHAPE FAIRED

Λ 0
 λ 10

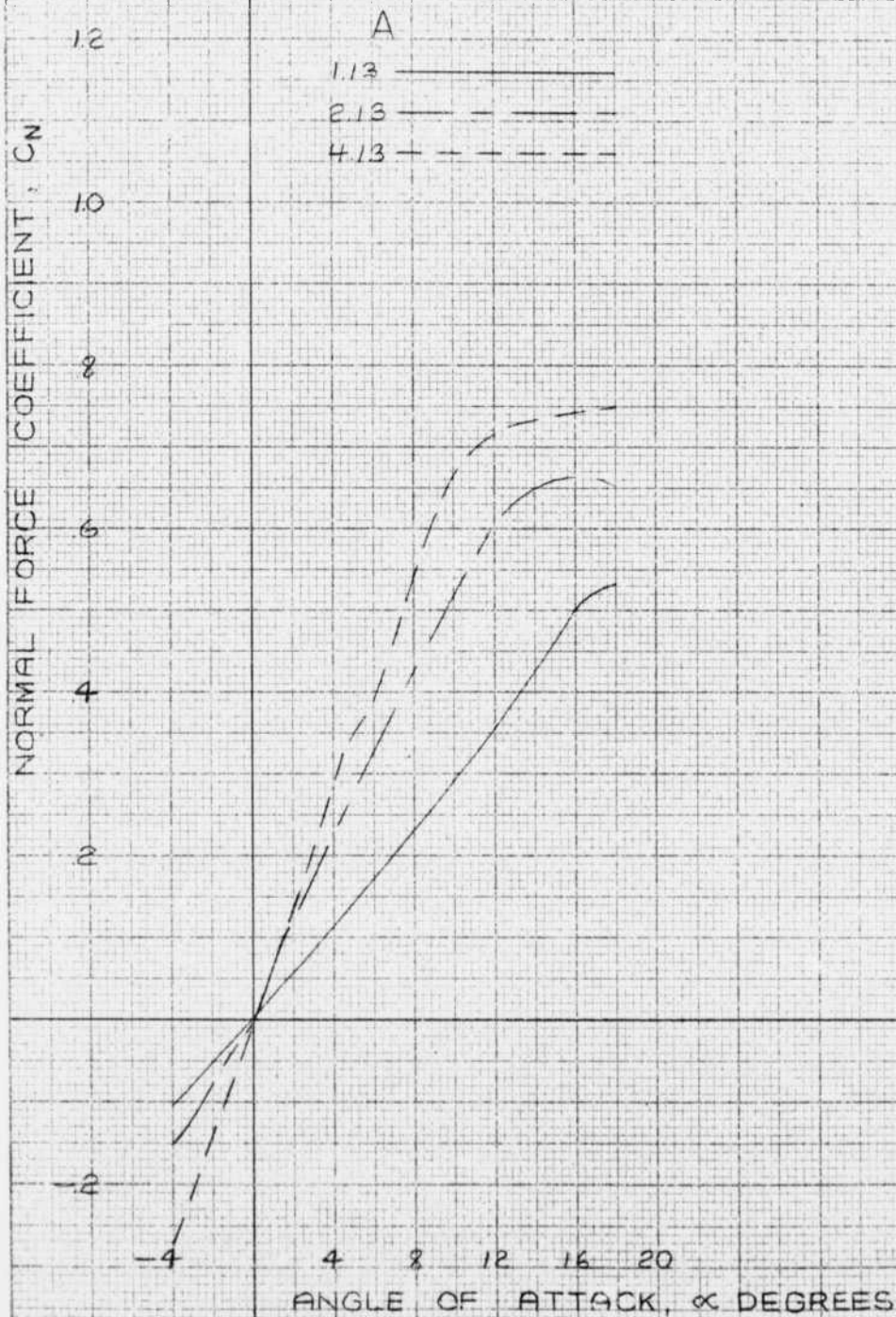


FIGURE 49C

SECTION NACA 64A010

TIP SHAPE FAIRED

Λ 0

λ 1.0

A

1/3 —————

2/3 — — — — —

4/3 - - - - -

RESULTANT FORCE COEFFICIENT, C_R

12

10

8

6

4

2

-4

4

8

12

16

20

ANGLE OF ATTACK, α DEGREES

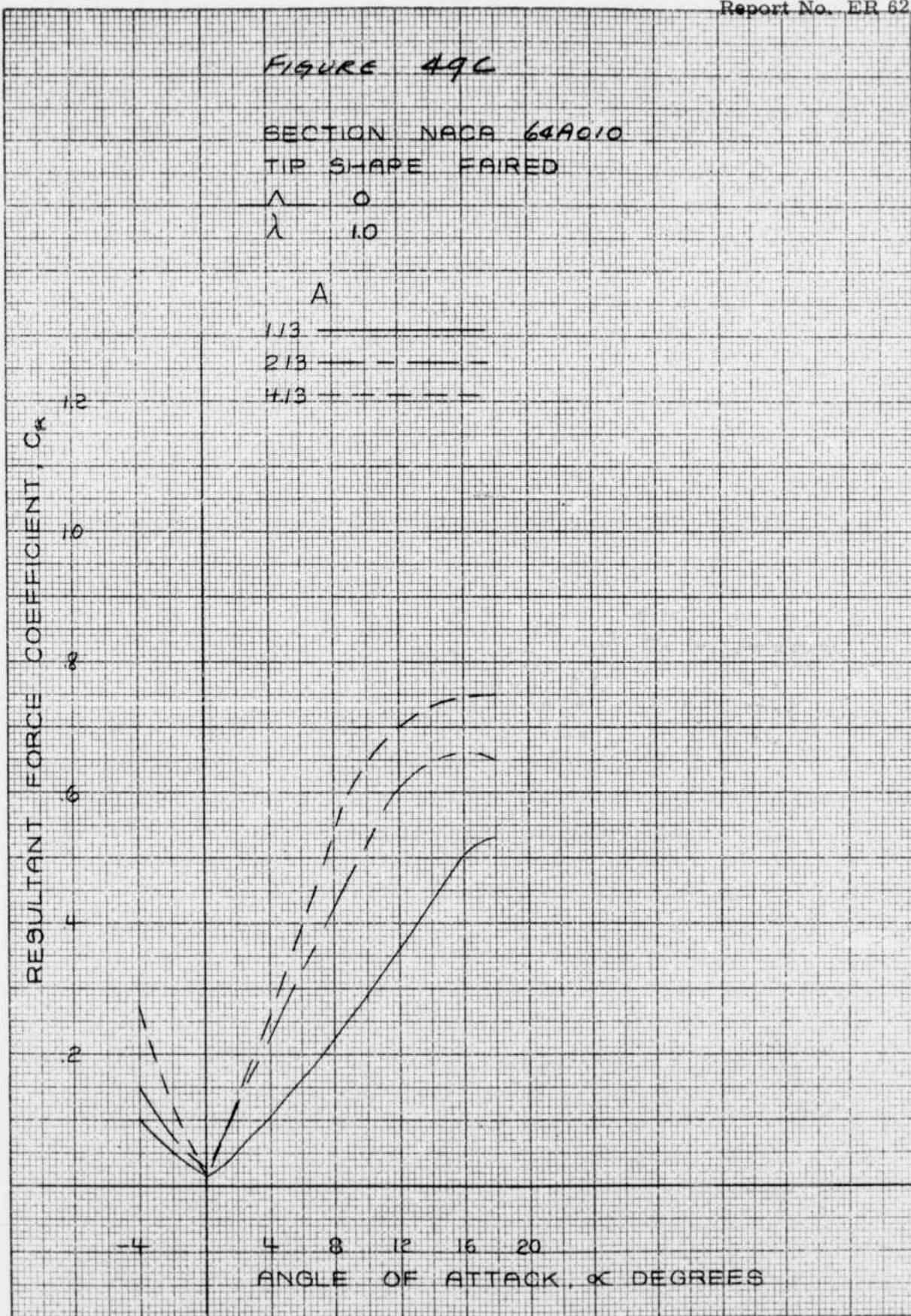


FIGURE 49D

SECTION NACA 64A010

TIP SHAPE FAIRED

Λ 0
 λ 1.0

A

1.13 —————
2.13 — — — — —
4.13 — — — — —

CHORDWISE CENTER OF PRESSURE
PERCENT OF CHORD, $C_{CP} \%$

30
20
10

4 8 12 16 20
ANGLE OF ATTACK, α DEGREES

